NEURAL MECHANISMS UNDERLYING MOVEMENT-BASED EMBODIED CONTEMPLATIVE PRACTICES

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NEURAL MECHANISMS UNDERLYING MOVEMENT-BASED EMBODIED CONTEMPLATIVE PRACTICES

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"Two Pyramidals", Enamel on composition gold leaf. Greg Dunn, 2010
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Relative to the extensive neuroscientific work on seated meditation practices, far less studies have investigated the neural mechanisms underlying movement-based contemplative practices such as yoga or tai chi. Movement-based practices have, however, been found to be effective for relieving the symptoms of several clinical conditions, and to elicit measurable changes in physiological, neural, and behavioral parameters in healthy individuals. An important challenge for neuroscience is therefore to advance our understanding of the neurophysiological and neurocognitive mechanisms underlying these observed effects, and this Research Topic aims to make a contribution in this regard. It showcases the current state of the art of investigations on movement-based practices including yoga, tai chi, the Feldenkrais Method, as well as dance. Featured contributions include empirical research, proposals of theoretical frameworks, as well as novel perspectives on a variety of issues relevant to the field. This Research Topic is the first of its kind to specifically attempt a neurophysiological and neurocognitive characterization that spans multiple mindful movement approaches, and we trust it will be of interest to basic scientists, clinical researchers, and contemplative practitioners alike.

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EDITORIAL
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Editorial: Neural Mechanisms Underlying Movement-Based Embodied Contemplative Practices

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The Editorial on the Research Topic

Neural Mechanisms Underlying Movement-Based Embodied Contemplative Practices

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INTRODUCTION

Compared to the extensive body of neuroscientific work on seated meditation practices, far fewer studies have investigated the neural mechanisms underlying movement-based contemplative practices such as yoga or tai chi. One likely reason is the inherent challenge of dealing with their multifaceted nature, typically involving specific movement sequences, regulation of the breath, and modulation of attention. Movement-based practices have, however, been found to be effective for relieving the symptoms of clinical conditions as diverse as cancer, Parkinson's disease (PD), chronic pain, fibromyalgia, post-traumatic stress disorder (PTSD), attention deficit hyperactivity disorder (ADHD), depression, and anxiety-related disorders. In addition, they have been shown to elicit measurable changes in physiological stress parameters, cognitive, and physical functioning as well experienced emotional states in healthy individuals. An important challenge for contemplative science is therefore to advance our understanding of the neurophysiological and neurocognitive mechanisms underlying these observed effects. The current Research Topic aims to make a contribution in this regard by outlining the state of the art of research on movement-based practices including yoga, tai chi, the Feldenkrais Method, as well as dance. The featured articles present empirical data, propose novel theoretical frameworks, and address the clinical implications of research within the field.

CONTRIBUTIONS TO THE CURRENT RESEARCH TOPIC

Movement-Based Embodied Contemplative Practices

The first section of this Research Topic features perspective as well as hypothesis and theory articles addressing general aspects of movement-based contemplative approaches. Schmalzl et al. present an introductory perspective article defining the concept of movement-based embodied contemplative practices (MECPs). Drawing from examples of various movement-based practices and modern somatic therapeutic techniques, the authors explore how they are grounded in the concepts of embodiment, movement and contemplation. The practices are viewed through the lens of an enactive approach to cognition, which postulates that mental functions cannot be fully understood without reference to the physical body as well as the environment in which they are experienced. Russell and Arcuri discuss clinical and research implications of mindful movement. Specifically, the authors address how regulation of attention and working memory relate to mind-wandering in the context of both mindfulness and movement training. In addition, they propose that for some clinical populations mindful movement may be more suited than traditional seated mindfulness techniques. Clark et al. examine the relationship between motor and cognitive functioning, suggesting that mindful movement approaches are of particular relevance for developmental disorders such as ADHD. The authors propose a model of skilled attention in which motor plans, attention, and executive function are seen as mutually co-defining aspects of skilled behavior, and discuss direct clinical implications of their theoretical framework. Lastly, Payne and Crane-Godreau delineate the concept of preparatory set (PS), referring to the coordination of largely sub-cortical mechanisms that underlie an organism's stress response. Such mechanisms include posture, autonomic state, affective state, attention, and expectation. The authors outline how mind-body approaches such as meditative movement and somatic education can be used to restore an adaptive PS.

Yoga

The second section of this Research Topic features hypothesis and theory as well as original research articles on yoga. Gard et al. present a theoretical framework and system-based network model outlining the mechanisms through which yoga may impact self-regulation and psychological health. The authors contextualize yoga in historical and contemporary settings, and describe the types of ethical percepts, physical postures, breath regulation, as well as meditative techniques that the practice involves. In addition, they outline how yoga may facilitate bidirectional integration between high- and low-level brain networks, and how this may impact cognitive, emotional, behavioral, and autonomic functioning under stress. Schmalzl et al. also propose a comprehensive theoretical framework of yoga-based practices (YBP), and discuss the main neurophysiological and neurocognitive processes hypothesized to underlie their effects. Specifically, the authors propose that compared to mindfulness-based practices, the rich set of movement, breath, and attention components employed in YBP may more directly engage the vagal afferent system, as well as basal ganglia and cerebellar circuits. In turn, YBP may have a more pronounced impact on autonomic, emotional, and cognitive regulation. Henje Blom et al. present a model for the treatment of adolescent depression informed by mindfulness-based therapy, yoga, as well as modern psychotherapeutic approaches. Their proposed Training for Awareness, Resilience and Action (TARA) takes the developmental limitations of top-down cognitive control in adolescence into account, and promotes bottom-up strategies such as vagal afference to decrease limbic activation and reduce allostatic load. It provides a comprehensive framework for a novel treatment strategy for adolescent depression, and constitutes a base for investigating the neuroscientific and systemic regulatory mechanisms of change in this condition. To conclude the theoretical portion of this section, Solomonova presents an opinion article exploring the concept of yoga as an intentional practice. She outlines the importance of studying intentional and first-person experiential aspects in the neurophenomenological investigation of MECPs, emphasizing various ways in which yoga may shed light on the contribution of intentional and dynamic bodily processes to embodied cognition. As for original research articles, Villemure et al. used magnetic resonance imaging (MRI) to compare age-related gray matter volume (GMV) decline in expert yoga practitioners and controls. Yoga practitioners did not display the typically amount of age-related GMV decline, and years of yoga experience were found to correlate with GMV in brain areas involved in autonomic regulation, emotional processing, and executive functioning. The authors interpret their findings to suggest that sustained yoga practice may have neuroprotective effects against age-related GMV decline. In a further neuroimaging study, Gard et al. compared whole brain resting state functional connectivity in experienced yoga practitioners, meditation practitioners and controls. Network based statistics revealed that, as a group, yoga and meditation practitioners had significantly greater connectivity between the caudate nucleus and numerous cortical regions. The authors conclude that increased functional connectivity within basal ganglia cortico-thalamic feedback loops may be a potential mechanism underlying improved behavioral and cognitive flexibility previously found to be associated with yoga and meditation. Lastly, Fiori et al. present a behavioral study investigating proprioceptive and vestibular processing as well as self-transcendence traits in a group of yoga practitioners and individuals with no yoga experience. The results of their study indicate that yoga practitioners have a higher degree of body awareness characterized by more reliance on internal bodily signals for behavioral regulation. In addition, they point to a potential correlation between body awareness and self-transcendence traits.

Tai Chi

The third section of this Research Topic features three original research articles on tai chi. Wayne et al. report the results of a clinical trial involving a tai chi intervention for older adults. Specifically, the authors investigated the impact of tai chi training on dual task gait parameters that are predictive of falls. The positive effects of tai chi training observed under cognitively challenging conditions support the value of neurophysiological research evaluating how mind-body practices like tai chi impact cognitive-motor interactions. Converse et al. investigated the effect of a tai chi program on self-reported and objectively measured attentional processes in healthy young adults. Outcome measures included self-reported levels of inattention and hyperactivity-impulsivity, as well as performance on a computer based response inhibition task. Both measures were positively impacted by the program, leading the authors to suggest that tai chi may hold potential as a non-pharmacological intervention for ADHD. Lastly, Kerr et al. present two studies evaluating the effect of tai chi on sensorimotor processing. The results of the first study, in which electromyography (EMG) was used to measure intermuscular coherence (IMC) in advanced as well as novice practitioners, suggest that tai chi practice elicits complex changes in sensorimotor processes over the course of training. The findings of the second study indicate that the amount of cumulative practice in tai chi practitioners is related to some aspects of their response to the rubber hand illusion (RHI), an experimental paradigm examining facets of body ownership and agency. Taken together, these studies provide an interesting platform for further investigations of how body-focused contemplative practices impact objective measures of sensorimotor processing and subjective experiences of embodiment.

Feldenkrais

The fourth section of this Research Topic is dedicated to an original article on the Feldenkrais Method, a movement-based learning method aimed at improving movement organization. Specifically, Verrel et al. used functional magnetic resonance imaging (fMRI) to investigate the short-term neural effects of two subtly different forms of a brief sensorimotor intervention adapted from the Feldenkrais Method. While increased resting state activity in motor areas was observed after both manipulations, their differential pattern suggested that specifically tailored sensorimotor interventions can selectively target lower level sensory areas related to specific body parts or instead engage more broad action related networks.

Dance

The final section of this Research Topic features an opinion article by van Vugt who explores the notion of classical ballet as a movement-based contemplative practice. Specifically, the author compares ballet to other contemplative practices on the dimensions of cultivation of attention, interoception, meta-cognition, and emotion regulation. Proposed hypotheses for the potentially different neural pathways involved in cultivating contemplation through ballet compared to other contemplative practices are followed by an outline of suggestions for future studies on the topic.

CONCLUSION

The current Research Topic aims to address the existing gap in our understanding of the neurophysiological and neurocognitive mechanisms underlying the effects of movement-based contemplative practices such yoga, tai chi, and modern somatic approaches. The featured original research articles report data probing the influence of movement-based contemplative practices on age related GMV decline, functional brain connectivity, sensorimotor processing, multisensory integration, gait parameters, body awareness, and cognitive control. The featured theory articles propose mechanistic models and hypotheses about (1) how movement-based contemplative practices may engage both bottom-up physiological and top-down cognitive processes, and consequently promote autonomic, emotional and cognitive self-regulation, (2) the relationship between motor and mental skills, and (3) the clinical implications of mindful movement. Lastly, the featured perspective articles aim to more clearly define key concepts such as movement, embodiment, contemplation, intention, and meta-cognition as they pertain to movement-based contemplative practices. We trust that the contributions will be of interest to basic scientists, clinical researchers, and contemplative practitioners alike, and hope it will inspire further research in the field.

AUTHOR CONTRIBUTIONS

LS wrote the manuscript, CEK provided critical feedback, and both authors have approved the work for publication.

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Movement-based embodied contemplative practices: definitions and paradigms

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Over the past decades, cognitive neuroscience has witnessed a shift from predominantly disembodied and computational views of the mind, to more embodied and situated views of the mind. These postulate that mental functions cannot be fully understood without reference to the physical body and the environment in which they are experienced. Within the field of contemplative science, the directing of attention to bodily sensations has so far mainly been studied in the context of seated meditation and mindfulness practices. However, the cultivation of interoceptive, proprioceptive and kinesthetic awareness is also said to lie at the core of many movement-based contemplative practices such as Yoga, Qigong, and Tai Chi. In addition, it likely plays a key role in the efficacy of modern somatic therapeutic techniques such as the Feldenkrais Method and the Alexander Technique. In the current paper we examine how these practices are grounded in the concepts of embodiment, movement and contemplation, as we look at them primarily through the lens of an enactive approach to cognition. Throughout, we point to a series of challenges that arise when Western scientists study practices that are based on a non-dualistic view of mind and body.

Keywords: Yoga, Qigong, Somatics, embodiment, movement, contemplation, proprioception, mindfulness

INTRODUCTION

Compared to the extensive body of work on mindfulness-based practices, far fewer scientific studies have examined the mechanisms underlying movement-based embodied contemplative practices such as Yoga or Qigong. One likely reason is the inherent challenge of dealing with their multifaceted nature, typically involving specific movement sequences, specialized use of the breath, and modulation of attention (Wayne and Kaptchuk, 2008). Movement-based practices have, however, been shown to alleviate the symptoms of various clinical conditions (Jahnke et al., 2010; Wren et al., 2011), and elicit measurable changes in physiological stress markers (Lee et al., 2004; West et al., 2004), cognitive functioning (Manjunath and Telles, 2001; Silva et al., 2007), sensorimotor acuity (Kerr et al., 2008), as well as emotional states in healthy populations (Chattha et al., 2008). An important challenge for contemplative scientists is therefore to advance our understanding of the mechanisms underlying these complex practices. But what exactly constitutes a movement-based embodied contemplative practice (MECP)? Contemplative movement systems exist in almost all cultures of the world—from shamanistic dances, Christian liturgical gestures, and Eastern spiritual practices, to modern Western somatic practices. The initial challenge in looking at these systems is one of providing a taxonomy that is appropriate both to the systems themselves and to thorough scientific investigation. Whether a system is embodied or not, whether it is movement-based or not, and whether it is contemplative or not, are all relevant distinctions, so let us look at each of these aspects separately.

EMBODIED

Over the past decades, cognitive neuroscience has witnessed a shift from predominantly abstract and computational views of the mind, to more embodied and situated views of the mind.

Francisco Varela (Varela et al., 1991) was one of the first to introduce the term "embodied mind" into cognitive neuroscience as a counter to the concept of a "disembodied mind," a mental entity considered independently of its relationship to a body and the environment (for further perspectives see (Wilson, 2002), and (Ziemke, 2003). According to the "enactive approach" to cognition (Thompson and Varela, 2001; Thompson, 2005; Di Paolo and Thompson, 2014), living beings are autonomous agents that actively generate and maintain their physical and psychological identities, and that enact their cognitive domains through their activities. As such, the enactive approach postulates that human beings exists intrinsically as embodied beings, and that mental functions such as perception, cognition and motivation, cannot be fully understood without reference to the physical body as well as the environment in which they are experienced (Varela et al., 1991; Thompson, 2007).

The closely related "grounded theory" of cognition (Barsalou, 2008) posits that cognition (including abstract thought, conceptual knowledge and semantic memory) is grounded in the brain's modal sensory systems, rather than being merely based on abstract computations. Similarly, the dynamical systems approach to developmental theory (Camras and Witherington, 2005), psychoanalysis (Krueger, 2002) as well as the newly emerging body-oriented methods of psychotherapy (Heller, 2012), all emphasize that bodily sensory systems are the first to develop and that they play a fundamental role in the formation of the sense of self (Sheets-Johnstone, 1999). In sum, all these schools of thought converge on the fact that the experience of one's self in the world as a cognizant being does not solely emerge from neural activity within the brain. Instead, it involves a complex interplay of brain, body and environment, and the seamless integration of interoceptive, proprioceptive (including vestibular), kinesthetic, tactile, and spatial information (Ehrsson, 2007; Haselager et al., 2012; Ionta et al., 2011).

Within the field of contemplative science, the process of becoming reflectively attentive to bodily sensations and sensory experiences has so far been primarily studied in the context of seated meditation and mindfulness-based practices (Didonna, 2009). However, it is certainly at the core of many movement-based practices as well. In fact, systems such as Hatha Yoga, Qigong, Tai Chi, the Alexander Technique, and the Feldenkrais Method (see Supplementary Material for a brief description of these systems), all involve an explicit emphasis on attending to interoceptive, proprioceptive and kinesthetic qualities of experience. They also use concepts such as "being in one's body" to encourage an embodied experience of the self.

MOVEMENT-BASED

One of the central motivations of examining movement within the context of contemplative practices can be related to the enactive approach described above. Movement is a fundamental characteristic of the embodied state, and the enactive as well as the grounded cognition approaches propose that the individual's capacity for self-movement and its underlying sensorimotor substrates are a constitutive part of all cognitive processes (Thompson and Varela, 2001; Barsalou, 2008). In addition, they propose that any embodied activity, including cognitive processes, takes the form of sensorimotor coupling with the environment. What a living organism senses and perceives is a function of how it moves, and how a living organism moves is a function of what it senses and perceives (Maturana and Varela, 1987). Along similar lines, Llinás (2002) echoes Sperry's earlier assertion (Sperry, 1952) that movement is the principal function of the nervous system, and that most advanced functions of the cortex can be seen as elaborations of the basic need to move toward or away from environmental stimuli. The word "emotion" is derived from the Old French "emouvoir" ("to stir up or agitate"), and from the Latin roots "ex-" (out) and "-movere" (to move). Similarly, the word "attention" is derived from the root "ten" ("to stretch out toward") (Partridge, 1966). In that sense, feeling attracted or repulsed from something, or even directing or withdrawing ones attention from something, can be seen as subtle forms of movement (Day, 1964; Sheets-Johnstone, 1999).

For the most part, MECPs are based on internally generated self-willed movement (Krieghoff et al., 2011), and practitioners guide and adjust their movement based on subtle feedback from joints and muscles (Scott, 2012). Such voluntary and actively initiated movement, as opposed to externally evoked or purely passively imposed motion, is intrinsic to the sense of agency (Kalckert and Ehrsson, 2012), which in turn is central to the development of the sense of self (Thelen and Fogel, 1989). Given their emphasis on carefully executed intentional movements, we speculate that MECPs can be a tool for restructuring an individual's sense of agency, and consequently impact the exploration and transformation their sense of self. There are, however, also forms of MECPs that involve spontaneous movement that is not controlled voluntarily (e.g., Spontaneous Qigong, Tandava, Shaktipat, Katsugen-Kai, Latihan, and Kundalini (Louchakova and Warner, 2003). Such practices involve putting oneself into a state of receptivity and surrendering to the spontaneous movement that arises. Overtly, these movements may resemble animal movements, Taijiquan forms, or Yoga asanas and mudras. In other cases however, the "movement" is purely internal, involving vivid interior sensations of heat, vibration, "energy" currents, and even changes in experienced bodily shape and spatial extension. During infant development, spontaneous involuntary movement precedes controlled voluntary movement and the development of a sense of agency (Sheets-Johnstone, 1999). That is, an infant's experience of "movement occurs" precedes the experience of "I move" (Haselager et al., 2012). We suggest that MECPs involving spontaneous movement may therefore allow a constructive regression to early stages of development of voluntary motor control, and a consequent re-modeling of the sense of agency.

Asian movement-based practices such as Ashtanga Vinyasa Yoga (Jois, 1999) or Taijiquan (Jou and Shapiro, 1983) obviously involve overt voluntary physical motion, and strongly emphasize specific forms and qualities of movement. However, let us consider this quote from Yiquan master Wang Xiangzhai: "One should know that a big movement is not as good as a small movement, a small movement is not as good as stillness, one must know that only stillness is the endless movement." (Wang, 2005). In Qigong practice, as in the internal martial arts, there is often a progression from an overt large motion, to a very small and subtle motion, to a purely internal or imagined movement—and this last is regarded as the most effective (as well as the most difficult) way of moving the "Qi" (life energy). So what needs to move, and to what extent does the movement need to be overtly evident, in order for a practice to qualify as movement-based? Here we propose the idea of extending the concept of "movement-based" so as to include very subtle, and even imagined, movement. This idea is supported by our knowledge of the neural mechanisms underlying motor control (Scott, 2012) and motor imagery (Schuster et al., 2011). Every execution of an overt movement controlled by the primary motor cortex is preceded by activations in premotor and supplementary motor areas. This preparatory phase has the purpose of organizing the movement by setting the appropriate posture, muscle tone and autonomic tone, and allow for integration of information from other cortical regions (e.g., visual, somatosensory, executive, affective and motivational) into the intended motor action (Wolpert et al., 2011). Moreover, premotor, supplementary motor as well as cerebellar areas are strongly activated during motor imagery without any actual physical movement (Gerardin et al., 2000), which in itself can improve motor skills and even physical strength (Yue and Cole, 1992; Sharma et al., 2006; Schuster et al., 2011). Qigong uses a technique very similar to motor imagery referred to as "moving the Qi." It consists of moving one's attention through the body so as to create a sensation of a flowing current of energy (Johnson et al., 2000). This form of practice is regarded by most practitioners as essential to the benefits of Qigong. We postulate that such subtle movement may have the effect of re-programming counterproductive patterns of intention and action by bringing the process of initiating action up to full consciousness.

At this point it might appear that every contemplative practice involves movement to some extent, and in fact we would argue that this is the case. Even in the most static forms of seated meditation the whole body is in constant subtle motion with the rhythm of the breath. That said however, we propose to define a movement-based practice as one in which the principal focus is on the intentional induction, or the intentional disinhibition, of overt movement or subtle internal sensations of movement. This definition excludes simply watching the breath while seated, unless specific emphasis is put on cultivating attention to the subtle movement that accompanies the breath.

CONTEMPLATIVE

In recent scientific explorations of contemplative practices, the terms "contemplation" and "meditation" have often been used interchangeably. The dictionary definition of contemplation includes both secular and religious meanings, referring to sustained attention and deep consideration of an object of interest that is often used in the context of religious or spiritual experience. The root of the word is the same as that of "temple"—"tem" or "to cut"—implying the concept of "carving out" a special time and place apart from daily preoccupations (Partridge, 1966). The word meditation has its origins in the Indo-European root "med," implying the concepts "to measure," "to consider," or "to think about." In Western Christian tradition "contemplation" refers to non-conceptual awareness of the Divine, whereas "meditation" carries the implication of conceptual, thought-based consideration of religious ideas. In the encounter between Western thought and Asian religions however, the English word meditation has come to be used to denote a wide range of diverse practices (for a discussion of this issue in relation to early Buddhist writings see Brooks, 2004).

A theoretical approach that is fundamental to the investigation of contemplative and meditative practices is neurophenomenology (Varela, 1996; Lutz and Thompson, 2003), an offshoot of the enactive approach described above. Neurophenomenology emerged out of the need to make systematic use of first-person methods and introspective phenomenological reports in the study of subjective conscious experience, and to relate the information gathered through those methods to complex dynamical systems analysis of brain activity. First-person methods, whether phenomenological, meditative or psychotherapeutic, are specifically aimed at increasing an individual's sensitivity to the quality of their experience from moment to moment. As a result, they have the potential to enable tacit, pre-verbal and pre-reflective aspects of the experience that typically remain merely "lived through," to become subjectively accessible. First-person methods exist within several contemplative practices and traditions that systematically cultivate the capacity for attentive self-awareness. While the individual practices differ in terms of specifically adopted techniques, they typically involve a disciplined process of becoming reflectively attentive to experience. In phenomenology this process is known as "epoché" (Husserl, 2012), and is described as three intertwining phases that form a dynamic cycle. In a nutshell, the three phases consist of suspension of habitual thoughts, redirection of attention to the experience itself, and receptivity to whatever arises from it (Depraz et al., 2000). In the context of MECPs, the redirection of attention predominantly entails cultivating awareness of bodily sensations and proprioceptive feedback related to the specifically employed movement and breathing techniques.

In recent years there has been an increasing interest in trying to understand the neural mechanisms underlying contemplative states. In fact, mindfulness-based meditation practices are now known to engage selective brain areas and neural networks involved in attention, body awareness, emotion regulation and the sense of self (Hölzel et al., 2011; Kerr et al., 2013). In addition, meditative practices have also been found to be typically associated with altered activation of the so-called default mode network (DMN) (Raichle et al., 2001), and enhanced connectivity between cortical regions implicated in self-monitoring and cognitive control (Brewer et al., 2011). The DMN is known to be involved in the construction of the "autobiographical self," and the assessment of stimuli for their relevance to the mentally sustained image of oneself. The altered activity of the DMN during meditative states has therefore been proposed to underlie a shift to less self-centered and more objective awareness of interoceptive as well as exteroceptive sensory events (Brewer et al., 2011). To which extent these finding also relate to MECPs remains an open question. Yoga and Qigong are broad and multifaceted categories, both including a range of "meditative movement" practices (Larkey et al., 2009), which are typically complemented by seated meditation techniques. Hence, while many of the already formulated theories about the mechanisms underlying traditional mindfulness-based practices might also apply to MECPs, it can also be assumed that MECPs may involve additional distinct mechanisms. Specifically, since movement increases the intensity of proprioceptive stimuli (Prochazka, 2011), it is possible that MECPs may offer a more efficient form of practice than seated meditation when it comes to cultivating bodily awareness and the sense of self.

Regardless of the specific underlying mechanisms, for most practitioners of MECPs contemplation represents the cultivation of sustained attention and equanimity (Desbordes et al., 2014), that for some has the ultimate aim of transforming habitual self-identity (akin to most seated meditation practices). However, MECPs can also be practiced without specific reference to altered self-identity as such. For example, Hatha Yoga can be practiced as a form of physical therapy, or Taijiquan purely as a martial art. Whether in such cases these types of practices can still be defined as contemplative remains subject to interpretation. In any case, the wide spectrum of potential applications of MECPs underlines the importance of documenting precisely which of their component parts are emphasized within a specific intervention—not only for the sake of scientific clarity, but out of respect to the systems themselves.

ADDITIONAL CONSIDERATIONS

So far we have referred to MECPs as performed by an individual person. However, there are also forms of MECPs involving two people. The relationship between these two may be that of master and disciple, teacher and student, therapist and client, or co-practitioners. Together, they enter a state of enhanced connectivity referred to as "resonance" (Siegel, 2007; Nummenmaa et al., 2012). In this state there is a largely automatically occurring sharing of affective and somatosensory experience, said to also involve a simultaneous activation of affective and sensory brain structures in both individuals. These phenomena have been documented in recent research in social neuroscience (Singer and Lamm, 2009). This form of dyadic contemplation is at the core of many Eastern movement-based systems (Wallace, 2001), as well as Western systems such as the Feldenkrais Method, the Alexander Technique, and body-oriented psychotherapy.

A further example of a novel therapeutic system that might fall into the category of MECPs is Somatic Experiencing (SE). Based on observations of how animals in the wild recover from trauma, its principal method is based on attention to bodily (interoceptive, proprioceptive, kinesthetic, tactile and spatial) sensations (Levine, 1997). According to SE theory, it is proposed that the practitioner is guided by the resonant relationship and verbally leads the client into internal and external movement, enabling a rebalancing of the autonomic nervous system (Levine, 2010).

CONCLUSION

As pointed out in a seminal article by Kerr (2002) and more recently by Payne and Crane-Godreau (2013), several challenges arise when Western scientists study practices that stem from ancient Eastern traditions. These authors underline the importance of having a thorough understanding of a system in its own terms before attempting to interpret it from a modern scientific perspective. They point out the risk of attempting to shoehorn a system into an already existing conceptual framework, which often eliminates the possibility of genuinely new discovery.

So what does it mean to look for the mechanisms underlying MECPs? Most of these practices have their own intrinsic complex bodies of theory. As both scientists and practitioners of MECPs, we are naturally drawn to wanting to operationalize them and understand them in our own "language." In doing so however, our aim is not to replace their already existing frameworks with new scientific explanations (Smolin, 2013). Rather, our task is one of translation—the translation of phenomena and theories emerging from one world-view into a language based on a very different world-view. Neither of these languages is right or wrong, but each of them has advantages and disadvantages. If neuroscience will remain open to encountering phenomena not previously recognized, this will undoubtedly improve our scientific understanding of human functioning and of how ancient practices can enhance human wellbeing in our modern times.

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SUPPLEMENTARY MATERIAL

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A neurophysiological and neuropsychological consideration of mindful movement: clinical and research implications

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In this article, we present ideas related to three key aspects of mindfulness training: the regulation of attention via noradrenaline, the importance of working memory and its various components (particularly the central executive and episodic buffer), and the relationship of both of these to mind-wandering. These same aspects of mindfulness training are also involved in the preparation and execution of movement and implicated in the pathophysiology of psychosis. We argue that by moving in a mindful way, there may be an additive effect of training as the two elements of the practice (mindfulness and movement) independently, and perhaps synergistically, engage common underlying systems (the default mode network). We discuss how working with mindful movement may be one route to mindfulness training for individuals who would struggle to sit still to complete the more commonly taught mindfulness practices. Drawing on our clinical experience working with individuals with severe and enduring mental health conditions, we show the real world application of these ideas and how they can be used to help those who are suffering and for whom current treatments are still far from adequate.

Keywords: tai chi, mindful movement, default mode network, mindfulness, working memory, attention, psychosis, locus coeruleus/adrenaline

Introduction

Mindfulness in its modern secular manifestation has been defined as the "the awareness that emerges through paying attention on purpose, in the present moment, and non-judgmentally to the unfolding of experience" (Kabat-Zinn, 2003, p. 145). This training has its roots in centuries old traditions, yet is now delivered in standardized mindfulness training protocols (ST-Mindfulness)[1] across a range of settings. This training in how to pay attention in a non-reactive, non-judgmental way is now well-established as beneficial for those suffering from chronic physical and mental health conditions (Fjorback et al., 2011; Williams and Kuyken, 2012; Khoury et al., 2013). However, one outstanding question relates to which specific components of this multifaceted intervention are contributing to the observed benefits (MacCoon et al., 2012; Williams et al., 2014).

A key training element is repeatedly attending to sensory information from the body. This is done through a variety of practices, which can be stationary (e.g., supine body scan) or moving (e.g., slow mindful walking, stretching, and yoga). The mindful movement practices may have a particular potency as evidenced by the finding that mindful yoga, although completed for the shortest amount of time relative to other practices,

[1]Including mindfulness-based stress reduction (MBSR) and mindfulness-based cognitive therapy (MBCT).

had the biggest impact on changes in mindfulness, well-being, and medical symptoms (Carmody and Baer, 2008). Mindful yoga practice time was also correlated with decreases in negative judgment of inner experience. Reduced judgment of inner experience contributes to changes in perceived stress in health workers (Shapiro et al., 2005) and reduced depressive symptoms in chronic depression (Kuyken et al., 2010). This indicates a strong rationale for mindful movement practices to be implemented more widely.

Most ST-Mindfulness practices require a certain degree of endurance in the ability to remain stationary for long periods, sometimes up to 45 min. This may be difficult for individuals who find it hard to remain seated and focused. Some of the groups who might therefore benefit from training based on mindful movement include: (i) those for whom the content and quality of mental experience is chaotic, disorganized, and distressing (e.g., visual or auditory hallucinations, paranoid delusions, racing thoughts and suicidal ideation, depersonalization); (ii) those whose illness may have compromised their attentional capabilities; (iii) those whose neurological or developmental disabilities make the metacognitive aspects of the training challenging; (iv) those for whom abnormalities (typically over-activity) in the motor system form part of the pathology of the disorder (for example ADHD, Tics, Tourette etc.); and (v) any others who find it hard to sit still for a relatively long period of time.

Mindful movement is a practice that may be of special relevance to those suffering from psychosis (and schizophrenia), an area of particular interest and specialization of the authors. High levels of stress are observed in these individuals. Not only do stressful life events predict relapse, there is also an effect of so-called daily hassles on relapse (Gispen-De Wied, 2000). One of the ways of coping with stress is to employ strategies. There is evidence that psychological interventions that deal with focusing attention and gaining control over mental experiences such as auditory hallucinations can reduce distress caused by symptoms (Shergill et al., 1998; Russell et al., 2008; Marsh et al., 2010). However, impaired cognitive performance may hamper this effort. There are a small number of studies using modified ST-Mindfulness protocols, and mindful movement with those experiencing psychosis (Russell, 2011; Chadwick, 2014), yet the wider delivery of mindfulness to these populations is hindered by beliefs that "mindfulness may be harmful for this client group" (Chadwick, 2014, p. 333).

In addition, the disorganized motor expression in this population has been neglected in current research. Often summarized and simplified under the term "agitation," neuromotor signs are a key developmental feature of schizophrenia (Schiffman et al., 2004). Psychotic patients often present with severe imbalances in posture, co-ordination, and movement refinement before pharmacological treatment (Pappa and Dazzan, 2009), reflecting the disturbance of homeostasis in both body and mind. A more detailed examination of mindful movements for this population may thus help to advance the understanding of the pathophysiology of psychotic phenomena.

In this article, we present an argument for the utility of mindful *movement* as a mindfulness training methodology. We suggest some reasons why this training method may be particularly helpful for persons with *severe and enduring mental conditions* who struggle with ST-Mindfulness exercises. Our starting point was the clinical observation that mindful movements are reported by these patients as easier relative to static practices (Russell and Tatton-Ramos, 2014). Considering the intensity of their mind-wandering experience (Whitfield-Gabrieli and Ford, 2012), we have identified some mechanisms that intersect ST-Mindfulness training, movement practices, and the clinical picture of psychotic patients. These may share neural underpinnings, including those brain regions[2] that are part of the default mode network (DMN), known to be disrupted in schizophrenia (Buckner et al., 2008; Hasenkamp et al., 2012; Whitfield-Gabrieli and Ford, 2012).

We are aware that we are proposing novel ways to look at phenomena observed both in mindfulness training and those suffering with psychotic symptoms. Our proposal offers some "pieces of a bigger puzzle," with obvious gaps between some of the concepts discussed. It is beyond the scope of this article to propose a coherent and tested theory for the complex field of consciousness and its disturbances observed in psychosis. However, we believe mindful movement is a powerful intervention and it is our intention to open avenues for research and clinical work, and further elaborate the multiple routes to mindfulness training.

Key Aspects of Mindfulness Training

A number of papers have proposed mechanisms underlying ST-Mindfulness and its effects [Shapiro et al., 2006; Teasdale and Chaskalson (Kulananda), 2011; Vago and Silbersweig, 2012], but scarce mention is made about these mechanisms with respect to the movement practices. While the *process* of mindfulness training is common to stationary and movement practices (paying attention, on purpose, moment-by-moment without judgment), the *object* (movement) has some distinct characteristics that may potentiate, as well as provide an alternative route to, mindfulness training.

Hasenkamp et al. (2012) defined four distinct phases to capture what occurs in the more basic type of meditation training (named focused attention): (i) mind-wandering; (ii) awareness of mind-wandering; (iii) an intentional shift of attention back to the object; and (iv) a sustained, focused attention on the object. They have suggested that mind-wandering engages the DMN, while the salience network (SN), and attentional networks/executive regions are engaged for the awareness of mind-wandering, the intentional shift of attention back to the object, and sustained focused attention (Hasenkamp et al., 2012). Mindfulness training results in a reduction of mind-wandering with a corresponding decrease in activation in the DMN (Brefczynski-Lewis et al., 2007; Pagnoni et al., 2008; Brewer et al., 2011).

Broadly speaking therefore, a key task in ST-Mindfulness is to monitor and regulate mind-wandering, by means of focusing attention on a chosen object. The basic features of this training are described in Section "Mind-Wandering." This process requires regulation of the locus coeruleus[3] (LC)/noradrenaline (NA)[4]

[2]The default mode network brain regions include four main areas: medial pre-frontal cortex, posterior cingulate and retrosplenial cortex, left and right inferior parietal lobule, and an additional region, the medial temporal lobe.
[3]The locus coeruleus, a nucleus in the pons (part of the brainstem) is the principal site for brain synthesis of noradrenaline.
[4]Also referred to as norepinephrine.

system (described in Section "Mind-Wandering and the Locus Coeruleus/Noradrenaline System"), and engagement of some of the components of the working memory system, specifically the central executive (CE) and episodic buffer (described in Section "Monitoring and Management of Mind-Wandering Requires Working Memory"). While these are only *some* of the components engaged in this complex mental training, they are particularly relevant here as they are also engaged in the generation and execution of movement (described in Section "Movements"). Thus, greater elaboration of these features may contribute to a further understanding of the mechanisms and effects of *mindful movement* practices. The commonalities between the neurophysiological and neuropsychological aspects of mindfulness training and movement, lead to a consideration of the additive effects of mindful movement (Section "Mindful Movements").

Mind-Wandering

Mind-wandering and task focus are often treated as a dichotomy (Schad et al., 2012). When trying to attend to an object, there is more opportunity to notice mind-wandering. Although we are often largely unaware that we have mentally "wandered off," one study indicates we are in this mode roughly 50% of the time (Killingsworth and Gilbert, 2010). The generic term "self-generated thoughts" has been proposed to capture this type of mental activity (Smallwood and Schooler, 2014). Mind-wandering can be intentional (e.g., planning, problem-solving, or reflecting), non-intentional (habitual), task-related or unrelated, and be of the "deep" (totally lost in thought) or "weak" (slight derailment) variety (Schad et al., 2012).

When attentional focus on the intended object wavers, there is an increased susceptibility to mind-wandering, and attention may be high-jacked by task-unrelated thoughts (TUTs). TUTs increase engagement with internal experience (including thoughts, images, memories) and reduce processing of external environmental events (Smallwood, 2013). The expression "lost in thought" describes the situation where we are no longer attentive to what is happening in the environment and are "up in our heads." Being lost in thought could be a pleasant experience, for example, a daydream about a holiday. Alternatively, it may be unpleasant and distressing, for example, caught up in endless cycles of ruminative judging. A consequence of mindfulness training is an increased ability to recognize and "catch" mind-wandering and an improved ability to switch between states of mind-wandering and focused attention (Lutz et al., 2008).

Mind-Wandering and the Locus Coeruleus/Noradrenaline System

Activity in the LC/NA system has been implicated in the occurrence of mind-wandering (as measured by TUTs, 27). The LC is a pontine structure, containing the largest number of noradrenergic neurons in the brain (Craven et al., 2005). It has extensive cortical projections, including to the pre-frontal cortex (Berridge and Waterhouse, 2003; Marien et al., 2004), an important feature which may underpin some of the cognitive effects of activity in this system (explained below). Employing two distinct modes of firing (phasic and tonic), the LC provides a range of arousal levels which optimize performance under different conditions (Smallwood et al., 2012). These patterns of firing modulate the system from states that are sleepy and dull to those of high arousal and excitability (see **Table 1**).

During awake states, low (tonic) baseline firing levels are associated with drowsiness and torpor. High tonic baseline firing rates are associated with increased arousal and distractibility. Importantly, there is an interaction between those two modes (phasic and tonic) and the ability to focus attention (Berridge and Waterhouse, 2003). In a narrow range of tonic firing, it is possible for the phasic mode to occur. This phasic mode modulates the salience of information, which directly manipulates the attentional focus.

In the phasic mode, there are brief neuronal discharges within the LC. These discharges are coupled with the onset of the cognitive processing of task-relevant events, resulting in the amplification of the cortical representation of task-relevant information (Smallwood et al., 2012). Increased discharge of the LC, results in increased NA in the system. Thus, NA has been suggested as a chemical modulator of attention (Posner and Rothbart, 2007) mediating two functions: (i) the ability to select and attend to information that is relevant to the task and (ii) the ability to be alert to unexpected task-unrelated events (Craven et al., 2005). Such modulation serves an adaptive function and is necessary for survival. It facilitates the detection of sensory information relevant to a task, making salient ("popping out") those stimuli that are aligned with the intention (see **Box 1**).

Increased tonic firing of the LC (with the resultant increase in NA in the system) disrupts this coupling process. Therefore, LC phasic responses become small or absent (Nieuwenhuis et al., 2005). This decoupling results in an "undifferentiated increase in cortical processing" (Smallwood et al., 2012, p. 2), meaning it is harder to distinguish between stimuli that are relevant and those

TABLE 1 | Locus coeruleus firing.

	Sleep wake cycle mode				
	Awake			Asleep	
LC firing mode	Tonic		Phasic	Tonic	
Arousal state	Hypervigilant	Torpor	Variable (partly dependent on tonic)	Slow wave	REM
Firing pattern/ NA level	High/increased	Low/decreased	Temporarily coupled to task-relevant processing	Low/decreased	Silent/ decreased
Cognitive/mental state	Distractibility	Dream-like	Focused, selective attention, filtering out information that does not pertain to the task	?	Dreaming
Patients	High tonic at acute states (positive symptoms)	More prone to mind-wandering (negative symptoms)	Attention deficits, planning deficits, faulty filtering	Disturbed sleep	

BOX 1 | Searching for your keys without stress – importance of locus coeruleus/noradrenaline system.

Example 1: Leaving home under calm conditions.

A common situation in daily life is leaving the house. When approaching the door, one realizes that the keys are not in their usual place, and begins to search for them.

With the intention to find the keys in mind, features of the desired object are drawn from memory (the color of the keys, the number of keys, the turtle shape of the key ring etc.) in a way that may be conscious or below conscious awareness. These features provide a template for the expected sensory information that will indicate the goal ("find keys") has been met. This template helps to filter the wealth of sensory information flooding into the system as you move your eyes, turn your head, or move your body to search the room. Any sensory information that does not match what is expected (colors "silver" and "bronze" associated with "metal," "small" etc.) is rapidly rejected. It is dimmed to the attentional system and the neural traces of information corresponding to these irrelevant items decays.

When there is a match between the expected and observed information (you see a turtle-shaped object) this is highly salient, you pay extra attention and go in for a closer look. This enhanced, focused attention allows you to reach your goal – you have found the keys!

In this case, the phasic mode of firing within LC allows the coupling of relevant information, giving salience to the searched sensory stimuli (e.g., silver, turtle shape) and dimming irrelevant information (e.g., another set of keys).

This system must be flexible enough to permit unforeseen situations. While you are searching for your keys, you may come across something that captures your attention outside of the current goal. For example, you notice that the cat's water bowl is empty. Depending on the relevance of this observation (how much you like your cat or how long you will be gone from the house), this sensory information may generate an alarm signal, which has the potential to disrupt the on-going task (find keys) and start a new one (fill water bowl).

BOX 2 | Searching for your keys with stress.

Example 2: Leaving home under stressful conditions.

Now imagine, trying to find your keys when you are running late, in a friend's house for the first time (unfamiliar territory), having already set the burglar alarm, under time pressure to get out before the alarm goes off. Under these conditions (high tonic firing of LC), our ability to search and detect the lost keys is compromised. Due to the increased levels of arousal, the possibility to match the incoming sensory information with the goal is diminished. You have to keep searching and going over the same areas repeatedly because of lack of salience (pop out) of the shape, color, or number of keys. This is distractibility, with diminished ability to focus attention on what is relevant.

that are not, nothing is "highlighted" or prioritized in terms of the attentional system (see **Box 2**). With increased NA activity, distractibility is thus magnified (Coull, 1994).

In mindfulness training, the task is to attend to the present moment (for example, attending to bodily sensations). The task requires an optimum state of "alert relaxation," with the student monitoring the level of arousal. The student is also instructed to focus attention on specific information (e.g., sensations arising from the body). Mind-wandering occurs: (i) when distractibility is high and it is hard to keep the focus of attention and (ii) when in a more relaxed state, stimuli from the outside world become dimmed and the mind is carried away by thoughts, images, and dream-like states, leading to torpor.

In terms of the LC/NA system, these would respectively correspond to higher or lower tonic modes [outside the narrow range that allows the phasic bursts to occur (Berridge and Waterhouse, 2003)]. In both these situations, there would be a decoupling of the transient bursts, which are necessary to keep the body sensations salient. This means other task-unrelated information becomes equally salient. In mindfulness training, the detection of mind-wandering is a cue to renew the intention to attend to the object of choice.

As proposed by Hasenkamp et al. (2012), meditation training in focused attention requires the student to become aware of mind-wandering, to shift attention away from it, and to re-focus on the intended object. According to this description, selection of the incoming stimuli (body sensations as distinct from a range of other stimuli) should be temporally coupled with the intended goal ("attend to the body"). This would require modulation of the LC/NA system. One suggestion is that phasic activity would be coupled to the sensory information related to the task (e.g., sensations arising from the body). Coupled LC discharges (and corresponding NA bursts) with body sensations would then result in these becoming amplified, and all other sensations (e.g., the thought that captured attention and took us off task) dimmed.

The sections above have described the putative neurophysiological underpinnings important for mindfulness training, describing how the different modes of LC/NA firing relate to states of arousal, mind-wandering, and focused attention. From a cognitive point of view, in focused attention meditation practices three skills are required: (i) monitoring and vigilance to distractors whilst maintaining the focus of attention on an object; (ii) prompt disengagement or release from distractors; and (iii) deliberate re-focusing of attention back to the chosen object (Lutz et al., 2008). In the following sections, we describe the cognitive model which enables these distinct and complex functions required for ST-Mindfulness, via processes that have been ascribed to the CE and episodic buffer components of the working memory system (Baddeley, 1986).

Monitoring and Management of Mind-Wandering Requires Working Memory

Working memory (and specifically its CE component) plays a key role in keeping clear priorities in the face of potential distractions (De Fockert, 2013). Therefore, during ST-Mindfulness, in order to keep the focus of attention whilst dealing with mind-wandering, such a system is very likely to be employed. A number of authors have implicated working memory in mindfulness training (Vago and Silbersweig, 2012) and its suggested therapeutic effects [Kerr et al., 2011; Teasdale and Chaskalson (Kulananda), 2011]. Experimental studies with both children (Schonert-Reichl et al., 2015) and adults (Jha et al., 2010; Mrazek et al., 2013) point to improvements in working memory capacity measured by neuropsychological tests following ST-Mindfulness. Under stressful conditions, short duration mindfulness training appears to reduce the deleterious effects of stress on working memory (Banks et al., 2015).

The term "working memory" falls within the broader construct of "executive functions," defined by Luria [cited by Shallice (1982)] as a specialized system for the programing, regulation, and verification of activity involving the frontal lobes. More recently, the terms control, inhibition, and monitoring are used to describe these key executive functions. In mindfulness training, attention and working memory functions share common features (Buttle, 2011). There are also many overlaps between attentional and working memory systems in the brain (Nobre et al., 2004; Buttle, 2011; Gazzaley and Nobre, 2012). This can create confusion and a lack of specificity in the use of the term "working memory" (Vago and Silbersweig, 2012) may hinder research (Raz and Buhle, 2006).

The centrality of working memory in behavior (D'Esposito and Postle, 2015) and cognitive control (D'Esposito and Postle, 2015) has been demonstrated in research spanning over 50 years in the fields of experimental psychology and neuropsychology, as well as clinically. Although models of working memory continue to be refined and developed, we believe the specificity of the multicomponent model of working memory proposed by Baddeley and Hitch (Baddeley and Hitch, 1974; Baddeley, 1986) may provide a useful framework to help develop and refine cognitive models of mindfulness training [Shapiro et al., 2006; Teasdale and Chaskalson (Kulananda), 2011; Vago and Silbersweig, 2012]. This robust model has survived extensive experimental testing over many decades (Baddeley, 2002, 2012).

Within Baddeley's framework, working memory comprises a CE with three auxiliary (slave) systems including the phonological loop, the visuo-spatial scratchpad (VSSP)[5], and the episodic buffer. Baddeley has stated that "*the episodic buffer can be accessed by the CE via the medium of conscious awareness*" (Baddeley, 2000, p. 421), making these two parts of this model particularly relevant to mindfulness training.

The CE co-ordinates information processing with the help of these auxiliary systems. Baddeley described CE as "*an attentional control system with no intrinsic storage capacity*" (Baddeley, 2000, p. 420). It maintains intention (goals), monitors conflict, has a number of attentional roles (switching between tasks, focused attention, and divided attention) and interacts (via the auxiliary systems) with long-term memory. All these activities are coordinated to keep us "on task." In ST-Mindfulness training, the CE is proposed to play a role in maintaining the overarching intention (e.g., "present moment awareness") and to guide the attentional system (e.g., "attend to breath").

The episodic buffer is described as a limited capacity, temporary, multimodal, storage system, which is at the interface between long-term memory and both the VSSP and phonological loop slave systems (Baddeley, 2000). The term "episodic" refers to a mode of operating, in which information is gathered together to form "chunks" or "episodes." The term "buffer" refers to the characteristics of this system to maintain information temporarily on-line in order to manipulate it, transforming different types of information from a variety of systems into a common multidimensional code.

[5]The VSSP integrates visuospatial information from multiple sources including visual, tactile, and kinesthetic, and from both episodic and semantic long-term memory.

Thus, when performing mindfulness training, we propose it is the CE which allows us to become "conscious aware" (as Baddeley describes it) of the contents stored in the episodic buffer (breath or not breath, the latter being mind-wandering) and to reallocate attentional resources back to the intended goal (breath).

To summarize, mindfulness training develops the ability to modulate between states of alertness and sleepiness, and the capacity to monitor mind-wandering and focus attention. It develops cognitive "top-down" control over mind-wandering and focused attention via the CE of the working memory system. It also engages the episodic buffering function to hold on-line multimodal information and allow it to be manipulated in the service of higher order intentions (and behavioral control).

In addition to the role of working memory, in Section "Key Aspects of Mindfulness Training," we have highlighted how the regulation of the LC/NA system is associated with mind-wandering which can interfere with the manipulation of attentional focus. We thus suggest that these two aspects are crucial to a better understanding of the mechanisms underlying the training of the focus of attention required in mindfulness meditation. In the following sections, we review evidence that moving the body engages these same systems (LC/NA and WM). What follows is not an exhaustive review of the motor sciences literature, rather we point to areas of overlap between motor movements and mindfulness training.

Movements

General Cognitive Aspects of Movement

A topic of long-standing interest to researchers studying both attention and movement is the variable ways in which attention can be brought to action, and the discovery that it is possible to attend to movement in a variety of ways and at different levels of conscious awareness (Norman and Shallice, 1986; Frith, 2002). Norman and Shallice (1986) model of the supervisory attentional system (SAS) aimed "to produce an explanation for the different types of experience one can have of an action" (p. 14). They described five instances where it might be necessary to bring attention to a motor task (see **Box 3**). In such situations, the SAS, interacting with attention, selects and co-ordinates the desired response motor sequence (Badgaiyan, 2000). Baddeley integrated the SAS into his working memory model, naming it the CE (Baddeley, 2012). It is the same mechanism, with two different names. It is a control system that can be used to manipulate the contents of working

BOX 3 | Five instances when it might be necessary to bring conscious attention to a motor task.

i) new movements
ii) movements in dangerous situations
iii) movements requiring planning or decision making
iv) movements requiring troubleshooting or correction
v) movements requiring overcoming habitual responses

*Note that all movements require planning/decision making and troubleshooting/correcting and that this does not *need* conscious awareness but conscious awareness can be brought to these aspects of the system.

memory storage in order to guide behavior in an effective way and particularly so when flexible responding is required (D'Esposito and Postle, 2015).

Automatic and Controlled Movement

The majority of movements made are highly automated and do not require any attention at all. Even a complex movement, like driving, can be done with little overt attention to the task (i.e., automatically). In this example, the mind is free to wander. However, it is possible to shift between automatic and controlled modes (in both directions). We argue that this process of shifting is inherent within the motor system, and in ST-Mindfulness occurs within an abstract mental realm. In ST-Mindfulness training, there is an intention to observe and undo habitual (automatic) mental reactivity in order to create new, healthier habits of responding (Kang et al., 2012). Thus, being able to shift between the automatic and controlled modes, via engagement of attention is important when training mindfulness. Moreover, this is also an intrinsic element of motor behavior, particularly when learning a new motor skill. The three-stage theory of motor learning proposes that after passing through the "cognitive" and "association" stages, we reach a third "automatic" stage (Fitts and Posner, 1967). In this automatic stage, the motor skill is so well-established that it can be performed automatically in a range of contexts with limited demands on attentional resources (as with the driving example above).

Shifting back into controlled mode (from automatic) can occur under a variety of circumstances (see **Box 3**) and with varying levels of awareness. This might be required if you were deliberately trying to reverse a habitual way of moving (for example, un-doing a bad habit you had picked up in your golf swing). Another example of shifting between these modes is when you encounter something dangerous in the environment, which requires a rapid modification of the movement, correcting the movement, the posture, and perhaps shifting back the intention. In this case, an alerting signal is provided by the system, something that may occur either without awareness or with delayed awareness. **Box 4** shows how the movement program has been modified by unexpected external circumstances some time before a conscious awareness of the need to modify the movement takes place. Ullsperger et al. (2010) have speculated that we are not aware of the error-detection, but rather become aware of the subsequent arousal response in the system.

BOX 4 | Automatic correction of automatic movements.

A highly automated program to walk forwards in a straight line can be carried out whilst doing many other tasks such as talking to a friend or looking elsewhere. We can execute these walking, talking, and looking motor commands automatically without allocating any attention to the motor elements.

Imagine that you are walking, with your head turned, attention elsewhere. You do not notice there is an obstacle (a rubbish bag) directly in your path. Before you are even consciously aware of the hazard, it is likely that your body will correct or modify the movement, allowing you to jump over or side-step the bag. Only after the movement has been corrected, we realize there was an obstacle. This conscious awareness has come much too late to modify the movement via controlled means.

Having had this experience, we might in future be more "mindful" when walking and talking to our friend. This everyday term reflects the element of attention that we bring to situations that might be dangerous, most famously heard on the London Underground ("Mind the gap").

Prediction and Anticipation in Movement

Information processing models (combining ideas from computer sciences and observations from physiology) detail how this process of rapid correction occurs. "*It is now generally accepted that when we execute a movement we predict the sensory consequences of that movement through generative or forward models (…) predicted kinematics from motor commands are considered an integral part of motor execution*" (Kilner et al., 2007, p. 161). The term corollary discharge (also called "efference copy") describes the "copy" or "template" of the predicted movement discharged into the system at the same time as the efferent motor command. This efference copy is drawn from stored memories of motor commands and their sensory consequences (Blakemore et al., 2001) and provides an internal representation of the expected sensory consequences of the movement.

The *observed* visual and proprioceptive sensations entering the system during the movement are compared against this efference copy on a moment-by-moment basis. This determines if the movement has been executed as intended (Jeannerod, 2003). If the observed sensory input (the reafferent signal) *matches* the efference copy, the movement has been conducted as planned, and there is no need to allocate attention. This process has been suggested as a way to increase the efficiency of attention and cognitive processing, by preventing the central nervous system from wasting valuable metabolic resources processing irrelevant (self-generated) sensory stimuli and maximizing the detection of the more important unanticipated or unpredicted stimuli (Pynn and DeSouza, 2013). In these latter cases (see **Box 4**), there is a *mismatch* between expected and observed sensory information, creating an error signal, and alerting the system to do something to modify the movement. In any movement, the mismatches are more salient. The error signal triggers a cascade of events including those that will reconfigure muscle activity, joint orientation, and velocity as well as top-down mechanisms to re-organize the movement sequence. Part of this process may involve bringing the source of the discrepancy into focus. This is an important feature of the motor system with survival value.

Environmental demands as well as changing internal goals mean we need to anticipate, predict, and process in parallel information related to our movements on a moment-by-moment basis. No matter whether the movement is well-practiced (highly automatic) or brand new, the brain creates simulations to anticipate the various stages of the movement, and the state of sensory receptors, in order to foresee possible solutions to every error, take chances, and make decisions (Berthoz, 1997).

The possibility to anticipate movements in the way described above may engage a type of simulation architecture that has been evoked in discussions of mind-wandering and the DMN. As Buckner has stated "*there may be specialized brain systems that underlie our abilities to mentally explore and anticipate future situations*" (Buckner et al., 2008, p. 31). Berthoz has also pointed to the importance of simulation in movement physiology and Jeannerod's work proposes a simulation hypothesis of motor cognition that underpins action representation, social cognition, and language understanding (Jeannerod, 2006). Although more research is needed to clarify whether these motor and cognitive simulation systems are the same, from a philosophical point of view[6], they appear to represent the same phenomena that "*the brain is continuously and unconsciously learning to anticipate the consequences of action or activity on itself, on the world and on other people*" (Timmermans et al., 2012, p. 1412).

In summary, motor learning models indicate how movement sequences can be highly automatic or fully conscious. Cognitive models suggest how movement commands interface with the attentional system to change our experience of an action under different conditions. Information processing models suggest how internal movement representations support flexible responding. The feedforward model is proposed to do this by predicting what we might expect to experience and then comparing this with the actual experience. In this latter system, an error-detection/alerting signal is activated when there is a mismatch that may have potential survival value. These error correction mechanisms in the movement system may rely on the same neurophysiological (LC/NA) and neuropsychological (WM) as we describe below.

Neurophysiological Aspects of Movement: LC/NA

The noradrenergic system is implicated in the physiology of movements; both the autonomic aspects of movements and the more cognitive aspects.

Movement requires autonomic adjustments, such as changes in arterial blood-pressure or volume and LC–NA neuronal activity is highly sensitive to cardiovascular events (Elam et al., 1986b). Additionally, during movement, there are an increased number and variety of tactile sensations (cutaneous sensory afferents), which feed into the LC (Elam et al., 1986a,b). These afferents include those arising from the skin stretching over muscles and the sensation of the air or clothes moving across the skin. Thus, movements are likely to impact on LC–NA firing rates, via modulation of cardiovascular and sensory afferents.

Any system that monitors salience must be intimately connected to the movement system in order to ensure that the animal survives when it detects something threatening, requiring it to escape from danger (Berridge and Waterhouse, 2003). This suggestion is supported by Bortoletto's observation (Bortoletto et al., 2011) that arousal does not directly activate structures underlying the preparation for actions, but rather influences the allocation of attentional resources to movement. As suggested in Section "Mind-Wandering and the Locus Coeruleus/Noradrenaline System," the phasic mode of LC firing supports task-relevant information processing and selective attention. It has been suggested that the output of LC activity may "*coordinately regulate the speed and efficiency of motor responses to salient stimuli*" (Berridge and Waterhouse, 2003, p. 61). The neuroanatomical and neurophysiological properties of the LC (Berridge and Waterhouse, 2003) make it suitable for signaling the detection of unexpected state changes (Dayan and Yu, 2006) and triggering the required rapid behavioral adaptation to an environment that is constantly changing (Bouret and Sara, 2005; Dayan and Yu, 2006) (see example in **Box 5**). The error signal ("mismatch" in the feedforward model, described above) is a salient marker of an unexpected change in the environment, which may prompt modulation of the LC/NA system.

BOX 5 | Pianist playing solo at a live classical music concert.

The pianist has a repertoire of well-prepared, highly practiced movements. These include sequences of whole body movements, foot movements, and more complex finger movements. These are well-learned movements. However, each live concert brings a unique set of circumstances, which is the combination of the sounds produced by the entire orchestra, unfolding over time. The pianist must not only play his part, but also "insert" it (the solo) within a wider context (an on-going orchestral piece). On the basis of this sensory information (primarily auditory but which may also include the conductors physical movements), the soloist needs to execute his actions (commencement of playing his part). In order to do it correctly, the pianist must integrate, with precise timing, the sensory information (music) with the movements he is executing to play his part. This coupling of sensory incoming information temporarily linked to the goal (planned movements to play the piano solo) requires the LC/NA system.

Although the exact mechanism by which the LC/NA system modulates movements has not yet been fully elucidated, it is likely an important neuromodulator, with the caveat that this system likely interacts with other neurotransmitters, such as dopamine.

Neuropsychological Aspects of Movement: Working Memory

The error correction process within the motor system has been suggested to imply a short-term storage of outflow information (Jeannerod, 1997), a function which could be subserved by the episodic buffer of working memory. We suggest these expected and observed sensory consequences are held, to be manipulated, within the episodic buffer system. The episodic buffer can hold multimodal information including representations drawn up from long-term memory (as would be necessary to hold all the different sorts information stored in relation to movements).

Working memory and movement programing share common processes, as indicated by studies where working memory demands have been increased, causing interference in the motor behavior. Increasing working memory load interferes with movement preparatory processes that involve cognitive control, suggesting that there is a shared resource for working memory and movement planning (Baker et al., 2011). Experiments that have explored the capacity of the VSSP under different arm movement conditions demonstrate that there is an overlap between the movement and the operation of this slave system (Quinn and Ralston, 1986). In both these studies, the effects were distinct from the effects of the experimental manipulations on attention.

Working memory is considered to play a role in the execution of motor programs that require discrete timing. Making a slow movement as we do in mindfulness requires more working memory as demonstrated by experiments showing that loading working memory interferes with slow, discrete movements more than it does with continuous, fast paced movements (Maes et al., 2015).

These findings described above would predict that movements requiring attention (engaging the WM system) will impact on mind-wandering. Teasdale et al. (1995) conducted a number of experiments to determine the relationship between working

[6]This is a large philosophical area of debate encompassing enacted cognition and embodiment that is outside the scope of this paper.

memory (specifically the CE) and a type of mind-wandering referred to as stimulus-independent thoughts (SITs). In a visuomotor task, the production of SITs was reduced when learning the task. This effect was seen to a lesser degree once the task had been practiced. These findings are consistent with the hypothesis that the production of SITs and the control and co-ordination of movements share (and compete for) the same limit CE resources.

In terms of possible treatment implications, Teasdale et al. (1995) suggest that "*the most effective tasks to block unwanted thoughts are those that make continuous demands on the control and co-ordinating resources of the CE, but, that do not, themselves, generate SITs*" (p. 558). This suggests that new movements, requiring attention, are able to interrupt mind-wandering processes. Mind-wandering can also be reduced with mindful movements, whereby focused attention is deliberately brought to any movement, including automatic ones. This finding is congruent with reports that there is a decreased in the DMN activity (and thus a possibility to reduce mind-wandering) when working memory is increased (Koshino et al., 2014). The critical point is the engagement of attention whilst moving. This is described in more detail below.

Mindful Movements

Both movements and mindfulness engage wide-ranging brain networks that modulate arousal, activity, attention, and monitoring. Neuroimaging research suggests many overlaps between regions engaged during movement and those used for working memory and selective attention, including a fronto-parietal circuit (Harding et al., 2014) which is also activated in movement sequencing (Rushworth et al., 2001; Bengtsson et al., 2004), motor timing (Bortoletto et al., 2011), motor preparation (Collins et al., 2010), and motor learning (Jueptner et al., 1997).

Movement alone is sufficient to engage WM and the LC/NA system, due to the obvious "change" in sensory information that can be observed (e.g., posture, balance, co-ordination, speed) creating elements that can become the focus of attention. There are a number of contemplative movement practices of Eastern origin (e.g., Tai Chi, Chi Gong, Yoga) and also Western somatic education methods (e.g., Feldenkrais, Eutonia) that promote, via their somatic focus and slow speed, mindful states (a moment-by-moment felt sense of the body). These have been referred to as "movement-based contemplative practices" (Schmalzl et al., 2014). Some of these have well-recognized physical (Jahnke et al., 2010) and mental (Wang et al., 2010, 2014; Payne and Crane-Godreau, 2013) health benefits and there is a growing interest in their ability to promote mindfulness (Nedeljkovic et al., 2012).

During a slow movement, the flood of sensory information becomes apparent. It is possible to feel the air across the surface of the body through sensory receptors, the movement of the joints via proprioceptive input, and notice how autonomic responses (e.g., breathing and heart rate) are constantly being adjusted. This increased sensory information increases the perceptual load on the system (as there are more sensations to observe). The extensive literature on load theory suggests that a consequence of this is decreased distractibility (Lavie et al., 2004). The ability to process distractors is related to working memory capacity, when this is increased it enhances the ability to deal with distractors promptly. Therefore, the ability to attend, and stay attentive, may be easier during movement (see Carmody and Baer, 2008).

However, in order for a movement to be considered part of "ST-Mindfulness training," i.e., training with the benefits of reducing stress and transforming automatic reactivity into adaptive responding, there is an additional cognitive element required. Contemplative movement practices *tend* not to deliberately engage the cognitive training elements (awareness of attention to the object or lack thereof). Specific guidance is required to bring attention to mind-wandering and the cognitive elements used to manage mind-wandering.

It is possible to do a movement and train in mindfulness simultaneously, using the moving body as the object of focused attention training. Recently mindful movement has been defined as "any movement conducted with full explicit awareness of intention, attention, and all the physical and mental sensations unfolding over time. Mindful movements are conducted with a stance of compassionate acceptance toward each and every experience including thoughts, feelings, memories, and emotions but especially bodily sensations" (Russell and Tatton-Ramos, 2014, p. 120).

When conducting a movement in mindful way, it is suggested that there may be additive effects arising from the double engagement of the systems trained in ST-Mindfulness via the movement programing and execution aspects and the focused attention/cognitive aspects, detailed in **Table 2**.

A critical skill developed in mindfulness training is the ability to observe experiences (sensory information, thoughts, emotions), as they unfold. The student is asked to monitor sensations from body *and* mind, on a moment-by-moment basis. The working memory system (via CE and EB components) supports the monitoring of this constantly updated information. Similarly, the temporal ordering required to execute a movement, and process sensations coming back into the system, uses the same monitoring function and the same working memory system. Therefore, mindful movements have a dual entry point to engage the monitoring function of the working memory system (Maes et al., 2015).

Another task in mindfulness training is to hold on-line and keep track of the "intention." The student needs to keep an active intention to pay attention, to monitor mental and physical experiences, and stay on task. For example, monitoring whether we are on task (attending to a movement) or not (thinking about dinner). There is a parallel process in the movement system. Jeannerod (2003) proposed that movement "*requires not only the simulation of the whole action and its consequence in the external world, but also the monitoring of the intention-related signals*" (p. 162). Movements require the on-going monitoring of the efferent motor commands and afferent sensory signals to ensure the movement is going as intended (Blakemore and Decety, 2001). Therefore, intentionality is embedded within any volitional movement (Jeannerod, 2003). Here, we again see that mindful movements may have a dual entry point into the working memory system via the monitoring of the intention.

Clinical Populations

In the state of mind-wandering, Berthoz and Petit have suggested that *"rather than fixing its gaze in the facts of the world, the subject is focused on mere representations. All mental states are already*

TABLE 2 | Distinctive guidance points between contemplative and mindful movements.

Main mindfulness instruction	General guidance points	Contemplative movement	Mindful movement
Awareness of sensations	Bodily sensations as objects for the attention (sensations related to autonomic response, skeletal and muscular aspects, pressure, tactile and visceral, proprioception, kinematics)	√	√
Awareness of the present moment (PM)	PM attributes of body, movement sensations, and breath	Implicit	√
	PM attribute of mental experience, e.g., emphasis on staying with the present moment (not getting lost in past or future thinking)	Not usually	
Awareness of attention	Deliberate awareness of the ways in which to move, shift, narrow, and widen the focus of attention to aspects of body and movement. Commentary on the quality of the attention (vivid, dull, agitated, stable, striving)	Not usually	√
Awareness of mind-wandering	Acknowledgment and suggested management of mind-wandering	Not usually	√
Awareness of intention (on purpose)	Purposeful, deliberate engagement with the intention to move the body, pay attention, be present, mindful	Can be (e.g., Tai Chi, Feldenkrais, continuum movement)	√
Awareness of non-judgment	A deliberate attitude of acceptance and gentleness to mental and physical phenomena. For example, psychological responses to learning new movements (frustration, elation, irritation, pride)	Implicit and in relation to the physical body rather than the mind	√

there, peacefully juxtaposed along the one and only homogenous plane of 'Mind' " (Berthoz, 1997, p. 14). Although it has been suggested that mind-wandering may have an adaptive function in the pursuit of long-term goals (Smallwood and Andrews-Hanna, 2013), this system can be engaged in maladaptive/pathological ways. In the clinical setting, extreme mind-wandering in the form of ruminations and recriminations is not peaceful, and can be experienced as distressing. We have discussed how modulation of LC firing is implicated in mind-wandering. The involvement of this system in psychiatric conditions is suggested by the clinical picture of many disorders (Yamamoto and Hornykiewicz, 2004; Yamamoto et al., 2014). For example, in individuals with bipolar, there are high levels of arousal and anxiety and correspondingly high distractibility and poor attention (Thompson et al., 2005; Kung et al., 2010). In generalized anxiety states, the ability to imagine and rehearse future scenarios is over-used and sometimes overwhelming (anticipatory anxiety). In depression, firing rates are low, leading to the clinical signs of reduced physical activity. Most psychiatric conditions have some pattern of disrupted sleep supporting the notion of LC abnormalities. In **Table 1**, a summary of the different modes of LC firing is shown with reference to what occurs in patient populations.

For a clinician interacting with psychotic patients, it is often difficult to define whether their experience is, at that moment, a hallucination (aberrant sensory processing), a delusion (aberrant thought processing), or both. At the physiological level, the boundaries between perception and belief are considered to be less distinct, with both being dependent on prediction. Confusion can arise when there is a failure to update inferences and beliefs about the world, arising from a discrepancy between predicted and observed sensations. This has been offered as an account of hallucinations and delusions (Fletcher and Frith, 2009). In the motor domain, this manifests as passivity phenomena (where self-generated actions are attributed to others). Reinforcing the importance of the brain's capacity to predict and compare constantly updated information, Berthoz, who has worked primarily in the field of locomotion physiology, suggests hallucinations may be a type of "waking dream," in which internal circuits that are used to simulate the consequences of action are functioning autonomously (Berthoz, 1997). Clinically, this corresponds to the observation of patients in psychotic states who appear to be living as if in an "internal scene."

This reality distortion (Liddle, 1987) may be due to a disturbance in the capacity of the brain to simulate and hold on-line a version of reality, with a failure to update information at a suitable pace and with a specific temporal order. The confusion between perceptions resultant from imagined scenarios and those from the external world may arise from over-activity in DMN (Buckner et al., 2008). Abnormal functional and structural connectivity between brain regions are considered a core feature of schizophrenia, with hyper-connectivity in the DMN seen in these patients (Whitfield-Gabrieli and Ford, 2012). This hyper-connectivity has been proposed to result in a propensity to be overly self-referential, poor cognition (working memory, executive functions), and poor social cognitive performance (Buckner et al., 2008; Spreng et al., 2009). The latter includes the ability to simulate or hold "in mind" the mental states of others, a critical skill for social interactions, known as theory of mind.

Below, two key neurophysiological and neuropsychological deficits seen in psychotic patients are further explored to provide an understanding of why mindful movements are helpful when working with this population and why adaptations are needed (the latter detailed in Section "Clinical Application of Mindful Movement: A Description of a Practical Experience with Psychotic Patients").

Impaired LC/NA and WM Functioning in Patients

Patients with schizophrenia are known to be highly distracted (Chapman, 1956; Hemsley, 1976) and with defective filtering mechanisms (Saccuzzo and Braff, 1986). These impairments in information processing may reflect disturbances in the noradrenergic system. Although a number of neurotransmitters are implicated in the pathophysiology of schizophrenia, there is growing evidence that disruption in the noradrenergic system is a key contributor (Lieberman and Koreen, 1993; Yamamoto and Hornykiewicz, 2004; Craven et al., 2005; Lechin and van der Dijs, 2005). There are correlations between increased levels of NA and relapse in these patients (Van Kammen, 1991), which appear to be independent of medication effects (Van Kammen et al., 2014). Also, evidence has been found for increased central NA output (Friedman et al., 1999), elevated cerebral spinal fluid-NA associated with states of over-arousal (Kemali et al., 1990), and dysfunction of NA receptors in pre-frontal cortex associated with cognitive impairments in these patients (Friedman et al., 1999).

As discussed previously, modulation of the LC/NA system is associated with different ways to process incoming sensory information. Thus, high tonic levels of LC firing are associated with decoupling of the NA bursts from salient stimuli, resulting in poor discriminability and increased distractibility (Smallwood et al., 2012). It has been suggested that boosting of task-irrelevant signals (high tonic mode) increases "the conscious expression of intentional thoughts that are not directly related to the current task" (Smallwood et al., 2012, p. 2). With this firing pattern, there is a reduction in perceptual input from external sources, and the individual may be absorbed in their own internal experience. This description corresponds to clinical observations of psychotic patients, lost in their own mental experience, who are also sometimes incapable of determining whether information is arising from an internal or external source (as is the case with hallucinations). Thus, one interpretation is that the natural tendency to mind-wander is amplified in these patients due to the high tonic firing rate of the LC. Furthermore, abnormal P300 (also called P3) has been described as one of the most robust markers of schizophrenia (McCarley et al., 1993). P300 is an evoked potential signal that occurs after novel and task-relevant stimuli have been processed. It is considered an electrophysiological correlate of the LC phasic response mode (Nieuwenhuis et al., 2005). These findings point to defective phasic modulation of NA in the LC in schizophrenia, in addition to the tonic abnormalities.

From a neuropsychological perspective, working memory deficits are a key feature of schizophrenia (Goldman-Rakic, 1994; Forbes et al., 2009) and a target for treatment (Lett et al., 2015). Working memory difficulties are even more pronounced in those with formal thought disorder, who show particularly striking decrements on tasks assessing both VSSP and verbal components of the working memory system (Arcuri, 2003; Arcuri et al., 2010). Clinicians struggle to support these patients adequately, as psychological treatments often require the very cognitive abilities that are impaired. This may also preclude ST-Mindfulness, as these practices require working memory.

Making the Case for Training Mindfulness with Patients Using Mindful Movement

In the previous sections, we have described two mechanisms, one neurophysiological (LC/NA system) and one neuropsychological (WM) implicated in the ST-Mindfulness training (and focused attention training). We have also described the involvement of these two mechanisms in movements, and particularly in mindful movements. We further pointed to evidence of impairment of these same mechanisms in psychotic patients, and the resultant implications for using ST-Mindfulness static practices with these groups. On this basis, it is clear why ST-Mindfulness may be difficult and/or unsuitable for patients with psychosis. These observations can help inform theory-driven adaptations for the delivery of mindfulness training, allowing these individuals to benefit from mindfulness, delivered via another route: mindful movement. Before we describe our experience of doing this work, we summarize the rationale for why we believe this method works.

In psychosis, there is an extreme level of mind-wandering (patients are highly distracted). When using movements as the object of attentional training for mindfulness, you are engaging the same brain architecture (anticipation/simulation) as is engaged in mind-wandering states. This, we suggest, leaves less room for positive symptoms as the mind-wandering "machinery" is occupied with movement preparation and execution. At the neural level, mindful movements in those with high distractibility possibly facilitates the switching away from the DMN and toward attentional/executive and SNs.

Awareness generally is problematic for these patients, most likely due to impairments in the CE/EB system. The concrete, physical sense of movements and their timing properties (a beginning, middle, and end of a movement) provide strong anchors against which to detect mind-wandering. It is easier to detect the difference between a concrete and an abstract sensations (movement sensation versus an inner voice) as compared to two abstract sensations (a thought and an inner voice). With respect to the timing aspect, it is easy to become aware that your mind has wandered off during a movement because a very obvious portion of a defined movement sequence would have been completely missed (escaped your attention) while you were "gone." With supportive guidance from the facilitator (shown in **Table 3**), awareness of general mind-wandering (e.g., thoughts about dinner) and symptom-specific mind-wandering (e.g., auditory hallucinations) can be trained. The differentiation between the target of attention (movement) and the distractors ("normal" mind-wandering and/or the more extreme symptom-specific mind-wandering) is made easier as it does not rely solely on engagement and monitoring of the internal world.

In psychotic patients, WM and LC abnormalities may present as a difficulty in holding on-line the intention to pay attention, holding on-line the intention to monitor, shift, and direct attention, and problems with goal-directed movements. When completing slow mindful movements, it is easier to shift attention back to the movement because it is being conducted in a controlled way (which requires attention) rather than automatically. In terms of the intentional shift back to the object, in mindfulness training, this is usually held "in mind" by the individual, but in psychotic patients this needs to be done via guidance. The guidance of the facilitator supports the working memory deficits (perhaps functioning as an external, auxiliary, working memory system).

Psychotic patients have high distractibility and problems in maintaining a sustained, focused attention on any object. It has been suggested above that this may be related to the reported abnormalities in the LC/NA system. Specifically, we suggested that high tonic LC firing rates are linked to high levels of arousal (which makes paying attention difficult) as well as phasic firing mode disruption (making selective focused attention problematic). These difficulties can be mitigated with the correct preparation of the environment and individual prior to practice and by specific guidance to support

TABLE 3 | Guidance for delivery of mindful movement for psychotic patients.

Main mindfulness instruction	Specific guidance modifications with patients
Awareness of sensations	Increased prompts due to poor attention and high distractibility Increased support for voluntary attentional shifts ("just keep bringing attention back to the movement") More specific guidance about the types of sensations that may be attended to Encouragement of self-generated alterations to movements and their sensory consequences
Awareness of the present moment (pm)	Ask to keep checking if the sensation they feel is the same moment-by-moment Exploring the suggestion that no two movements are the same Reminders that each movement is a brand new "present moment" Exploring the temporal qualities (beginning, middle, and end of movements) and pacing of the movement sequences
Awareness of attention	Acknowledgment of increased mind-wandering Acknowledgment of the effort required, and that this will improve with practice (using the gym/muscle training analogy) Repeated reminders to monitor where the attention is at any given moment
Awareness of mind-wandering	Indicate that mind-wandering is normal Treat all mental experiences as equivalent to physical sensations (including "abnormal" or distressing mind-wandering such as voices, imagery etc.) Point to categories and types of mind-wandering
Awareness of intention (on purpose)	Repeated reminders about the intention to attend Reminders about why this practice is helpful Prompts to attend to the intention to move
Awareness of non-judgment	Repeated reminders about the intention to be gentle with physical and mental experiences Reminders to be gentle in response to distressing symptoms Supporting and encouraging any attempt at a movement (no right or wrong way to move) Reminders to be gentle with self and others

BOX 6 | BMT class structure.

(1) What Participants Do

The class is roughly 45–60 min during which gentle movements of all the major joints and a number of short tai chi sequences are conducted. The sequence of movements is a relatively flexible and can be adapted depending on the clinical characteristics of the group and the setting conditions.

The method is flexible in that it can be delivered to an open, rolling class as well as a semi-structured, cumulative teaching group. For the latter, teaching materials (handouts and stickers) are included for participants so they can take home and reflect on the key learning points, and have a visual prompt to remind them (for example) to slow down and attend to the body throughout their day.

(2) How They Do It

(a) Start moving: participants initially observe a movement (for example, a backwards arm rotation) and copy the instructor, completing the movement in whatever way is possible (with an emphasis on finding what they can do, rather than what they cannot).
(b) Move mindfully: once they have the general gist of the movement, they are instructed to follow the more detailed guidance of the instructor to the best of their ability.

Several aspects are emphasized:
(i) the mental activity related to the intention to move;
(ii) the specifics of the execution of the movement;
(iii) the sensory consequences of the movement;
(iv) the mental activity on-going during the movement.

In terms of mindfulness training, made explicit in the teaching of the class are the five principles of BMT:
(i) Go slow and see what happens
(ii) Engage with the activity intentionally
(iii) Pay attention
(iv) Learn more about yourself
(v) Be kind to self and others

attention from the facilitator. The moving body provides rich (and perhaps novel) sensations to support focused attention and reduce distractibility (as proposed by load theory).

Clinical Application of Mindful Movement: A Description of a Practical Experience with Psychotic Patients

In the following sections, we share our experience of working with adults with severe and enduring mental health conditions, offering mindful movement classes to inpatients in various settings. These observations arise from work on the development of a mindful movement protocol called Body in Mind Training (BMT; Russell, 2011; Russell and Tatton-Ramos, 2014) designed by one of the authors (TR, see **Box 6**). BMT uses a series of movements, many of which are derived from tai chi, performed with directed attention. This training has been developed primarily in the mental health setting, both with acutely ill and more stabilized community patients.

There are three aspects of what happens in this class, which may explain the beneficial effects observed. One is the care taken to support a down-ward shift in the tonic levels of arousal (from high to low). The second is the use of slow body movements, engaging (and competing with) the same simulating system as is engaged in mind-wandering. The third is the guidance of the facilitator, providing an auxiliary working memory system (holding intention, altering the mind to mind-wandering, guiding them back "on task").

Creating Environmental and Psychological Conditions to Reduce Arousal

Individuals in psychotic states are suspicious, frightened, feel persecuted, and their sensory perception is distorted (e.g., hallucinations). **Table 1** shows the underlying neurophysiology of these high levels of arousal. Extra care is therefore needed to create a suitable physical and psychological space for this work. In terms of environment, these groups are best delivered in a relatively quiet and well-ventilated area, ideally off the ward. A gym environment is ideal as it helps to frame this training as something one might do in everyday life (rather than being seen as a "treatment"), it encourages those who might be reluctant to attend a "mindfulness" or "meditation" group, and may increase the chance that these practices are continued following discharge from hospital.

Participants have commented that music helps them to settle when coming from busy ward/urban environments, and additionally that it helps to mask some of the distracting environmental sounds. Although typically music is not used in mindfulness classes, in this setting, it can help reduce arousal levels by serving as a noise filter. Music might be turned off halfway through the class in order to deliberately explore what happens in the mind (to attention and mind-wandering) when there are more distractions.

From a psychological point of view, the instruction in ST-Mindfulness to sit still, in silence and with eyes closed, is not ideal for psychotic patients and may even increase distress. The requirement to copy the facilitator's movements requires visual attention, so eyes must (initially at least) be open. Encouraging the spirit of curiosity and experimentation, participants can be invited to experiment with eyes open or closed, if they feel comfortable to do so.

In mindfulness training, a critical step is the personal decision to choose to engage with mental and physical experiences in a different way. In these classes therefore, there is a chance to explore personal responsibility and engagement with self and one's actions. Participation is explicitly voluntary, with each participant responsible for their own level of engagement. This may provide a rare therapeutic opportunity for autonomy. Participants can lie down, sit down, take a break, and regulate their involvement; the only rule is to be considerate of others in the class. There is thus a high degree of flexibility in delivery, which allows participants to find their own way to start moving mindfully. Modeling gentleness in every instruction and response is extremely important to counteract the aggression these individuals are experiencing internally (e.g., the negative and derogatory comments in auditory hallucinations).

Learning and Performing Movement Sequences

In BMT, some of the movements may be familiar (for example, a "swimming backwards" arm movement) while others might be new sequences of movements (moves adapted from Tai Chi such as "wave hands like clouds"). New movements require engagement of working memory and attentional focus (as described in Section "Movements"). When introducing new movements, there needs to be enough challenge without being overwhelming. Scaffolded learning methods (Young et al., 2002) can be used, with the facilitator providing "step down" options if the full movement sequence is not possible for either cognitive or physical reasons. Participants are encouraged to modify, adapt, slow down, or do whatever is necessary to get into the sequence, but to keep on trying, with each movement a new opportunity to start again. An unexpected observation in these classes was the way self-efficacy was developed when participants supported each other to learn new sequences. During the learning phase, the non-judging component of mindfulness needs to be strongly emphasized.

The transition between movement sequences tends to be much quicker, in order to combat the increased potential for mind-wandering and hold the attentional focus. **Table 3** shows some specific guidance points related to holding attention on sensations and working with mind-wandering. New and familiar movements may be interwoven throughout the class and new movements revisited to provide experiences of different levels of mental effort (and a chance to notice different types of mental reactivity).

Some participants may not be able to do the movements slowly, so they are invited to play with the pacing of the movements. Changing the speed brings automatic movements into the controlled mode and results in different kinematics and sensory experiences. Optimally, movements are conducted slowly and gracefully, however the main invitation is to notice how sensations can be different at different speeds.

Specific Guidance

Participants are first invited to copy the movement of the instructor in order to get the general gist of the movement. Copying movements may reduce the cognitive demands engaged in planning and executing movement via automatic engagement of the mirror neuron system, known to be activated when we observe others moving (Rizzolatti et al., 2009).

Participants are additionally given specific, frequent verbal guidance. This guidance supports the dysfunctional working memory by alleviating the requirement for the patient to hold their intention (to move, to attend, to shift, and re-orient attention to the body) in their working memory system. The use of frequent verbal prompts helps to orient attention and the moving body is the object for the attention. In this way, "top-down" cognitive support is provided (see also Chadwick, 2014).

Suggested guidance modifications are shown in **Table 3** and are framed around Kabat-Zinn's definition of mindfulness. The guidance points to what you might attend to in the movement [including sensations from the body, movement features as well as the things that might capture attention (internal/external distractions)]. This allows a detailed description of bodily sensations and movement processes alongside guidance that helps participants to see it is possible to hear a voice or experience an image, and without denying or fighting it, gently moving their attention to the body and returning to the present moment. Prompting an adjustment of posture or suggesting a modification to the movement helps to re-orient the individuals' attention and de-couple from the mind-wandering.

A specific difference between this training for these patients in a mental health setting and what might occur in a "community" contemplative movement class, is the acknowledgment within the guidance of the mental experience of these participants (rapid thoughts, high arousal/anxiety, disorganized thinking, and distressing imagery or voices). Developing this type of strategy to work with positive symptoms like auditory hallucinations has been suggested as a key intervention (Shergill et al., 1998). For example, saying "noticing if the mind is distracted by internal dialog, voices, or imagery and without judging that experience, trying your best to come back to the sensation of the movement of the shoulder blade, noticing the speed, the effort, any places of tightness or ease." This instruction is much more detailed in comparison to a more traditional guidance, which might say invite participants to "just notice the mind-wandering and bring it back to the body."

In summary, these clinical observations of the delivery of mindful movement to psychotic patients speak to the face validity of the theoretical ideas. The *"how"* of these mindful movement sessions is different from a typical contemplative movement class; the delivery is adapted, the movements are adapted, and the modified guidance is critical. It has been suggested that delivery of mindfulness in any format to individuals with severe and enduring mental health conditions requires a facilitator who is experienced not only with mindfulness, but additionally with psychosis and psychological therapy (Chadwick, 2014). In BMT, movement experience is also required.

Discussion

Summary

Based on the literature, this article has highlighted some candidate processes (neurophysiological and neuropsychological) that are likely implicated in mindfulness training using movements. A case for an essential role of the LC/NA system and working memory (particularly the CE and the episodic buffer components) has been made. We hypothesized that these components may be directly involved in maintaining the focus of attention within intended goals and staying within the experience, as it unfolds moment-by-moment. We described evidence from the literature that the moving body also engages the same neurophysiological and neuropsychological systems. A distinction was made between contemplative movements and mindfulness movements on the basis of the explicit training of attention and insight into mental experiences (e.g., mind-wandering) that occurs in the latter. Below, we draw together evidence from the neuroimaging literature to support the suggestion that the distinct phenomena of "meditating," "moving," and "experiencing psychotic symptoms" are associated with activity in certain (similar) brain networks (including the DMN, the SN, and an attentional/executive network). We propose that training with mindful movements engages these networks via a different route, one that is possible for those with schizophrenia, as detailed in our clinical observations (Section "Clinical Application of Mindful Movement: A Description of a Practical Experience with Psychotic Patients").

We have described the role of the DMN in mind-wandering and how activity in the DMN activity can be diminished via meditation. DMN activity may also be reduced when working memory load is increased (Koshino et al., 2014). Working memory load is increased when planning and executing movements. Therefore, mindful movement is likely to be associated with reduced activity in the DMN. Engaging working memory via mindful movement also places demands on the attentional/executive and SNs. Shifting between these networks (states of mind-wandering versus attending to movement) is thus required when moving in a mindful way. For this reason, the combination of movements with mindful attention meditation training may be particularly effective to reduce mind-wandering, whilst training the focus of attention.

The ability to engage and disengage DMN, SN, and the attentional/executive networks may involve phasic activation of the LC/NA system, to facilitate flexible responding in the face of ever-changing environmental conditions (Bouret and Sara, 2005). In schizophrenia, the LC/NA system is dysfunctional, and there is evidence of impairment in these three networks (Palaniyappan and Liddle, 2012; Whitfield-Gabrieli and Ford, 2012; Orellana and Slachevsky, 2013). Poor switching between internal and external foci of attention may also contribute to the observed cognitive impairments (Whitfield-Gabrieli and Ford, 2012). We thus suggest that impairments in flexible and adaptive responding, requiring the integration of stimuli from internal and external sources, via modulation of these three networks (DMN, attentional/executive networks, and SN) is impaired in psychotic patients and may arise from LC/NA system deficits. Palaniyappan and Liddle (2012) have suggested that the SN has a role pivotal to shifting between these networks. However, our clinical experience shows that mindful movement may, with modifications, be able to mitigate the impact of these impairments and provide a route to mindfulness training.

Hyper-connectivity in the DMN (described in Section "Clinical Populations") has also been associated with the cognitive abnormalities and positive symptoms seen in schizophrenia. These patients are highly distractible and lost in their inner world, paying little attention to external sensory information. They also have impaired working memory. For these reasons, mindfulness training needs to be adapted, in a way that takes into account the underlying disrupted mechanisms (and consequent impaired performance). We have spoken about the extra guidance requirements to support this training (**Table 3** and Section "Specific Guidance"). The additional guidance operates as a top-down support for movement planning and execution. This may partially compensate for executive functioning deficits in these patients (operating as an auxiliary working memory system) and modulate the attentional/executive network. Similar methods (directing attention to the relevant features to be observed) have been used to improve performance on a facial emotion recognition task in schizophrenia (Russell et al., 2008; Marsh et al., 2010).

The hyper-connectivity in DMN is also associated with problems inferring the mental states of others (theory of mind). Theory of mind develops from the natural capacity of the brain to simulate the intentions of others on the basis of observed movement (Blakemore and Decety, 2001), and is impaired in schizophrenia (Russell et al., 2006). This simulation system, associated with the DMN (Buckner et al., 2008; Spreng et al., 2009) may thus be engaged during mindful movement as participants observe and copy intentional movements. So, in addition to the top-down support provided, the requirement to observe and copy movements may offer a different (bottom-up) entry point into these same systems.

Possible Research

There remain however, a number of outstanding questions, which may provide avenues for future research. Investigations may be conducted at a variety of levels of explanation (neurophysiological, neuropsychological, clinical).

At the level of neurophysiology, one research avenue would be to test more formally whether mindfulness training will change the tonic and/or phasic firing rates of the LC/NA system. A second avenue might be to explore whether mindful movement training will impact on the DMN and/or other network activity in a way that is different from ST-Mindfulness. Static and movement-based interventions matched for every aspect by except movement might be compared in healthy participants. Distinctions were also made between contemplative and mindful movement trainings and these could also be compared, both at the neurophysiological and psychological levels.

From a psychological point of view, we have touched on a number of theories that may explain why movements provide a potent attentional focus. Incoming sensory information from the body during movement is different from that experienced during static practices. Using load theory as a framework (in both healthy and psychiatric patients), the differential effect on distractibility could be tested.

Baddeley's model could provide a framework to explore the benefits of mindfulness training on working memory. Tests of working memory (and its different sub-components) could be administered to meditators of different levels of experience (and including those who may come from contemplative movement traditions, or who have been trained in mindful movement). Tests of working memory could also be administered to patient groups who are undergoing different types of mindfulness training (movement, non-movement) to determine the malleability of this cognitive impairment and determine if there is any enduring effect of the training. Baddeley's model, although suggested to process multimodal representations, does not explicitly refer to multisensory information coming from internal sources (e.g., the body); it is not clear how sensory information from the body gets into the working memory system and/or is transformed into a higher order representations (Quak et al., 2015).

From a clinical point of view, given the link between NA, stress, and relapse, another avenue might be to determine whether a mindful movement program can help to prevent relapse (monitoring admissions or clinic visits for example) or increase compliance in other therapies (perhaps via an adjunctive effect). Furthermore, given that the illness of schizophrenia includes motor abnormalities, a further line of research might look at changes in measures of gait and movement kinetics following training in the deliberate, mindful engagement with the movement process.

Finally, as with ST-Mindfulness training, the effects of being in a group, sharing experiences, the experience of the facilitator and the non-judgmental space in which to explore the self are all likely contributors to the experience. In order to determine which of these factors are essential to any observed benefits, and delineate the relative contribution of content and process, dismantling studies would need to be conducted (Williams et al., 2014). These types of studies compare tightly controlled conditions to tease out the relative contribution of each of the components (for example, offering movements alone without sharing of experience, varying the experience level of the facilitator, or offering the training in a group versus individual format). In order to measure the efficacy of any mindful movement program, it will be necessary to tease apart the effect of movement, mindfulness, and then the combined effect of moving mindfully.

Limitations

One limitation in this work is the ability to measure accurately changes in the felt sense of the body (Mehling et al., 2009). Although mindfulness training increases the window of consciousness with respect to movement, there are still core impenetrable elements of movement that lie well out of the reach of awareness (as described in **Box 4**). The measurement of body awareness is highly problematic in healthy participants, and perhaps even more so in psychiatric populations. However, this does not preclude measurement of clinical and/or cognitive outcomes following mindfulness training.

Another important issue is how best to address the flexibility inherent in the delivery, and whilst still offering an effective and replicable outcome. Measures of both physical and cognitive change may be useful in this respect and help to disentangle aspects that are core to the efficacy from those that might be interchangeable.

Conclusion

Ultimately mindfulness training is a way to help manage more skillfully no matter what the experience. Therefore, as is the case in the wider mindfulness research field, an alternative strategy is to find out what is helpful about these interventions from participants directly, gathering qualitative information to understand what is really making the difference in their lives as a result of these practices. We end with an anecdote from a participant who suffers from schizophrenia who had been attending a drop-in mindfulness movement class. After practicing mindful walking, he was able, even when experiencing paranoid thoughts, to leave his home and go to the shop to buy milk to make a cup of tea. On that short journey, he maintained his attention on his feet, and his body as he moved, step by step, and managed to do something that previously would have been impossible. Even such a small thing that most of us would take for granted, can make a huge difference for these clients. Our intention with this article is to stimulate ideas and research that can continue this work.

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Conflict of Interest Statement: Tamara Anne Russell is the creator of the Body in Mind Training Program, which is a group mindfulness training program offered in the private sector. Silvia Maria Arcuri declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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Mindful movement and skilled attention

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Bodily movement has long been employed as a foundation for cultivating mental skills such as attention, self-control or mindfulness, with recent studies documenting the positive impacts of mindful movement training, such as yoga and tai chi. A parallel "mind-body connection" has also been observed in many developmental disorders. We elaborate a spectrum of mindfulness by considering ADHD, in which deficient motor control correlates with impaired (disinhibited) behavioral control contributing to defining features of excessive distractibility and impulsivity. These data provide evidence for an important axis of variation for wellbeing, in which skillful cognitive control covaries with a capacity for skillful movement. We review empirical and theoretical literature on attention, cognitive control, mind wandering, mindfulness and skill learning, endorsing a model of *skilled attention* in which motor plans, attention, and executive goals are seen as mutually co-defining aspects of skilled behavior that are linked by reciprocal inhibitory and excitatory connections. Thus, *any* movement training should engage "higher-order" inhibition and selection and develop a repertoire of rehearsed procedures that coordinate goals, attention and motor plans. However, we propose that *mindful* movement practice may improve the functional quality of rehearsed procedures, cultivating a transferrable skill of attention. We adopt Langer's spectrum of mindful learning that spans from "mindlessness" to engagement with the details of the present task and contrast this with the mental attitudes cultivated in standard mindfulness meditation. We particularly follow Feldenkrais' suggestion that mindful learning of skills for organizing the body in movement might transfer to other forms of mental activity. The results of mindful movement training should be observed in multiple complementary measures, and may have tremendous potential benefit for individuals with ADHD and other populations.

Keywords: attention, skill, ADHD, cognitive control, inhibition, movement, Feldenkrais, mindfulness

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Introduction

A growing body of literature demonstrates that mindful practice of movement can yield improvements in cognitive and attentional skills in healthy adults, and similarly improve functioning in "anomalous" development, as with ttention Deficit Hyperactivity Disorder (ADHD; Hernandez-Reif et al., 2001; Balasubramaniam et al., 2013; Converse et al., 2014; Gard et al., 2014b; Wayne et al., 2014). Moreover, individuals diagnosed with ADHD exhibit correlations between executive, attentional and motor deficits, providing evidence for a shared functional and neural basis (Gilbert et al., 2011; MacNeil et al., 2011). Existing accounts have provided candidate cognitive and neural mechanisms for this "mind–body connection" (Mostofsky and Simmonds, 2008; Tang and Posner, 2009; Vago and Silbersweig, 2012; Gard et al., 2014a), but given that these practices are based on movement, it is surprising that the role of motor learning remains underexplored. Following Marr (1982), we argue that it is critical to organize a neural theory, here of a mind–body connection, in light of the computational problems being solved, and the kinds of representations or algorithms that appear to be employed (see also Wilson and Golonka, 2013). Given the strong evidence for a relationship between movement skill and attentional and other forms of cognitive control, we propose that this relationship stems from profound overlap between the computational problems being solved in motor learning and executive function. Here we provide a theoretical view on the applied concern of how movement learning interventions might improve cognitive functioning in humans from the "computational" perspective of skill learning.

We begin with the common observation that *attention moves*. Attention moves via movement of the body, involving for example the eye, the head, or the arm, either in response to an attractive (exogenous) stimulus or as part of an internal (endogenous) impulse. While studying attention in isolation from physical movement has yielded notable progress, multiple lines of evidence now suggest that the process of controlling attentional movement cannot be cleanly separated from the selection of *physical* movements. Even "pure" *covert* shifts of attention, without movement of the sense organ, have been modeled as a planning state of ocular or striate (body) muscle movements that are not (yet) executed (Posner, 1980; Rizzolatti and Craighero, 2010). This somewhat radical conception dispenses with the need for distinct neural circuits for motor planning and spatial attention (but see Smith and Schenk, 2012).

A shared foundation for both sensory and motor function is reflected in the macro architecture and functioning of the brain (Anderson, 2010). Both motor planning and attentional control share a dependency on the same kind of information: contingencies regarding the structure of the environment, the body, and how they relate in behavior. Evolutionary and developmental evidence supports the foundational nature of sensorimotor coordination in the brain, where the earliest short-range primary motor-sensory connections are those that control simple movements, later developing premotor-parietal connections control more complex motor sequences, and still later developing long-range connections involving prefrontal and posterior parietal cortices support more complex or abstract sensorimotor interactions that may be extended over space and time (Fuster, 2001). Thus, much of cortical function may be characterized as a hierarchy of sensorimotor control that is roughly reflected in the elaboration of frontal (motor, premotor, prefrontal) and parietal cortices, along with additional subcortical inputs (cf. Cisek and Kalaska, 2010). We propose that the effects of mindful movement practices on attention may be understood within a theoretical framework for the mind–body connection that situates attentional and executive control within this sensorimotor hierarchy. Much as motor decision processes may be the result of reciprocal inhibition and excitation both within and between cortical representations, higher-order cognitive processes such as attentional control or response switching may likewise result from competitive selection among sensorimotor representations (cf. Smith et al., 1999; Fuster, 2001; Cisek and Kalaska, 2010). We propose that core shared features across attention and motor control provide the mechanistic basis for the effects of mindful movement practices.

Movement illustrates the inseparability of mind and body, and we propose that the traditionally "mental" phenomena of executive and attentional control are essentially "higher-order" motor control. MacKay (1982) observed that abstract skills organize existing procedures into the structure of higher-order skills. Computationally, if learning takes place under conditions of variability and uncertainty, these higher-order procedures will more readily transfer beyond trained contexts (Mitchell, 1997; Bishop, 2007). The results of motor task variation may be modeled as "structural" learning of those parameters for control that are shared across tasks (such as cycling and motorcycling) from those that are specific, resulting in a lower-dimensional space of common control parameters that foster transfer of a skill (Braun et al., 2009). A critical distinction is made between such higher-order skills and "core" or relatively modular motor control. Core motor control implements motor intentions while correcting for errors or binding immediate contingencies (Shadmehr et al., 2010; Wolpert et al., 2011), while higher-order motor control is described as integrating across multiple cognitive domains within a hierarchy of abstraction (Fitts and Posner, 1967; MacKay, 1982; Beilock and Carr, 2004; Wulf, 2007; Clark and Ivry, 2010) or as emerging from the interaction between mind and the physical world (Barsalou et al., 2007; Anderson, 2010). Intrinsic to skilled action is the deployment of goals and attention, which in well-trained skills may proceed without explicit intention, effort or even conscious awareness (for example, as when you mindlessly drive home in your car, instead of to your intended destination). Executive goals have been observed as embedded within hierarchically organized associations and procedures that can realize the goal (Miller et al., 1960; Baddeley, 1996; cf. "knowing how" in Cohen and Squire, 1980), or as emergent from the interaction dynamics of feedback loops in dynamic accounts of cognition (Kelso, 1997; Scherbaum et al., 2012). The mind–body connection might thus be viewed as the ubiquity of motor skill processes across different levels of abstraction, with transfer being facilitated by structural learning of generalizable control parameters.

Paradigm "failures" of attentional skill are the phenomenon of mind wandering and behaviors observed in attention-deficit/hyperactivity disorder (ADHD). Folk notions of mind wandering may focus on insufficiencies in the effort to maintain or return our attention to the sensations and actions relevant to our desired goals. While external distractions may certainly attract attention away from longer-term goals, mind wandering can also be the result of internally generated "distractions" as potentially unintended executive goals dominate or inhibit task-relevant goals (for evidence that goals arise automatically, see Bargh and Ferguson, 2000). We propose that such competition between goals might similarly explain aspects of ADHD. Specifically, impairments in attentional control and response inhibition—diagnostic features of the disorder—are likely driven by an inability to regulate competition between task-relevant and other internally or externally generated goals. There is strong evidence for impaired temporal discounting in ADHD, and available data indicate that this is due to dysregulation as opposed to differences in the perceived value of delayed rewards (Scheres et al., 2013) such that impaired ability to maintain focus appears to result from an excessive bias towards short term rewards that distract from longer term goals. These behavioral and neurologic findings reveal an "anomalous" pattern of development in ADHD that appears to affect fundamental mechanisms of cortical selection and inhibition in both the control of attention and of physical movement (Aron and Poldrack, 2005; Mostofsky and Simmonds, 2008). Integrating cortical mechanisms of selection and inhibition into our sensorimotor theory of the skilled control of attention, we thus speculate that selection and inhibition across goals, attention *and* motor plans may be a core feature of both ADHD and mind wandering.

If implicit or automatic goals are implicated in dysregulated attention and behavior, they may also be implicated in mindful attention and behavior. Scholarly descriptions of *mindfulness meditation* however, often centrally feature the element of an intentionally (and initially, effortfully) sustained mental state, particularly in focused attention (FA) meditation (e.g., Hasenkamp et al., 2012; Kerr et al., 2013; for a more inclusive overview, see Vago and Silbersweig, 2012). MacLean et al. (2010) in particular report improvements in sustained attention (i.e., likely decreased mind wandering) in a randomized assessment of intensive meditation training that included FA as well as other practices. By contrast, Langer (2000) provides a conception of mindful learning that is not achieved via effortful focus on a fixed mental state, but rather by engagement with evolving distinctions and alternatives as they arise within a context and task. We argue that mindful *movement* practice encourages mindful learning driven by awareness of sensorimotor distinctions and alternatives. While Langer avoids claims regarding the domain of meditation, we claim that mindful movement should expressly *not* be considered as a variant FA during movement (this approach is termed "contemplative movement" and is discussed elsewhere in this issue; Russell and Arcuri, 2015). We suggest that effort or sustained attention may be less necessary in training attentional skills via a mindful movement practice (though they are sometimes used), as sensorimotor activity may generate conditions for engagement (or "mindful presence") in learning from within the movement task. The natural co-occurrence of perceptions and movement may thus alleviate the problem of investing effort to establish a skill that one does not yet know how to perform—for example if the relevant procedural goals and coordination are not yet in place for the coordination of mindful attention (Feldenkrais, 1972; Kuhl, 2000). Movement *reliably generates* concretely observable sensations that can act as suitable feedback to support the discovery and refinement of relevant action, which is crucial for the training of both self-regulation and skill (Kuhl, 2000; Shadmehr et al., 2010; Strehl, 2014). By attending to movement *intentions* (i.e., goals) and actual *consequences* (i.e., distinctions in the sensation) of movements, value-based learning may efficiently strengthen or weaken associations to respective executive procedural representations. Thus, we propose that mindful movement may train control skills that can coordinate goals, attention, and motor programs (**Figure 1**)—particularly in cases wherein the learner may struggle in his intentions due to dysregulated mechanisms of cortical inhibition and selection, as in ADHD or other developmental challenges.

We suggest that Feldenkrais (1947) pioneered a "contemplative" or "neurophenomenological" (Thompson et al., 2005) approach of disciplined first-person inquiry and third-person explanations in his attempt to understand human development via a neural information processing theory of movement. As with meditation (Lutz et al., 2007), rigorous first-person insights from movement practice provided Feldenkrais with insight and constraints on the kinds of representations and procedures that must be instantiated in the nervous system. As such, we will in part rely on the ideas of Feldenkrais as a starting point for our discussion of the mechanisms of mindful movement practice below. We thereby do not intend to give a full account of mindful movement practices, but selectively evaluate how mindful movement may provide conditions for learning skills for attentional control. As with other skills, we propose that skilled control of attention requires inhibitory and excitatory associations between executive, sensory, and motoric representations that are coordinated within a repertoire of procedures. Critically, learning will generally occur in the context of existing, stable procedures, or "habits" that arose during development and adult life (Feldenkrais, 1947). Following Feldenkrais' suggestion, we focus primarily on learning via differentiating novel sensorimotor skills within the landscape of sensorimotor dependencies rather than on the extinction of existing habits (for a similar view, see Barandiaran and Di Paolo, 2014; Di Paolo et al., 2014; for an account of extinction in mindfulness meditation, see Vago and Silbersweig, 2012).

In summary, the theoretical construct of a repertoire of functional procedures and the rich characterization of stages and mechanisms of skill learning may be a novel and constructive application of concepts from the motor skill literature with broad applicability to more seemingly "cognitive" skills. Given our notion of attentional and executive control as higher-level skill processes within a sensorimotor network, we suggest that the exceptionally rich, stable sensory feedback generated by motor practice provides ideal conditions for the practitioner to develop skills for improved attentional and behavioral control. Hence, while our characterization of attentional and executive skill would imply that mindful movement practices and meditation target similar "learning

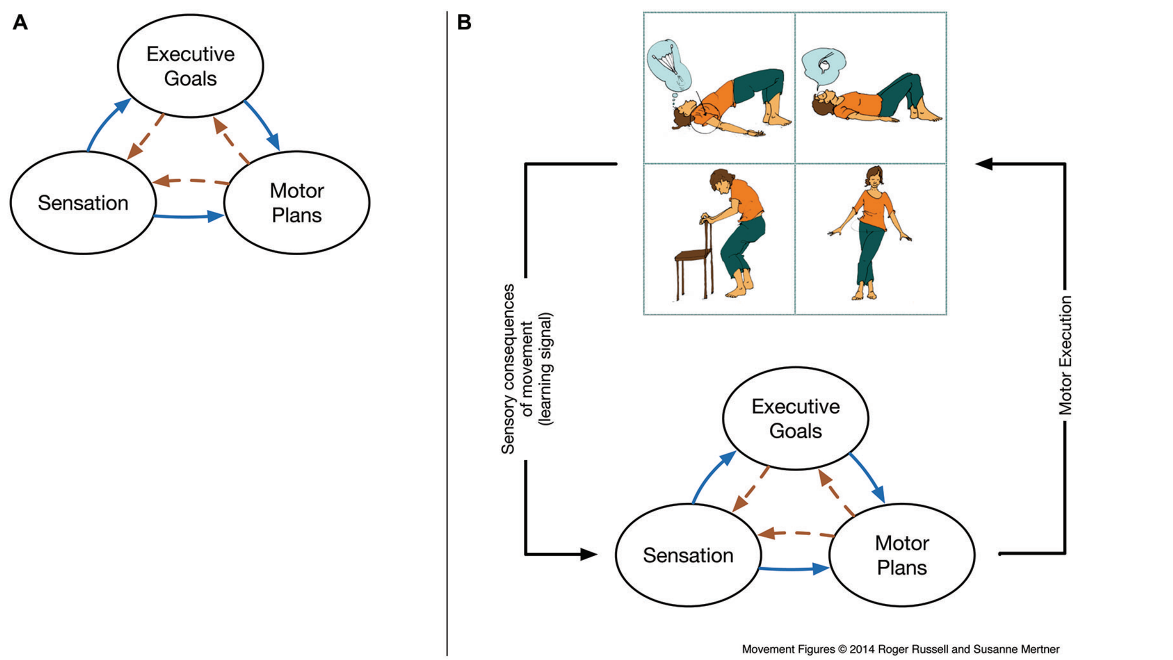

FIGURE 1 | (A) Schematic of reciprocal inhibition and selection between sensory, motor, and executive functions (adapted from Smith et al., 1999). "Feed-forward" connections from sensory and executive goal representations (solid blue, left-to-right) are a standard part of even the most simplistic models of sensorimotor control. More recent connectionist and dynamical systems approaches highlight that reciprocal connections are the norm throughout the nervous system (i.e., including dashed orange, right-to-left connections), giving rise to more complex dynamics. Thus, functions such as "attention" or "behavioral control" arise via coordinated interactions between evolving representations (we refer to this coordination as a procedure). The types of representation depicted here are likely supported by distributed brain networks and not fully dissociable, and we argue that sensorimotor control activity serves to coordinate and organize between these networks. **(B) Embedding sensory, motor and executive functions within the sensorimotor loop.** Here, enacting volitional or habitual motor plans continuously generates concrete, immediate and differentiated sensations via the body and world. These signals can be compared with states that are desired (via goals) or predicted (via motor efference). Hence, procedures of skilled coordination of reciprocal mechanisms of inhibition and selection underlying skilled attention and skilled cognitive control can be refined directly within the sensorimotor loop. This yields the profound potential for improvement of selection and inhibition processes, in particular in populations diagnosed with ADHD where impaired motor inhibition/selection is a diagnostic feature. Movement figures reprinted with permission from Russell (2014).

outcomes," movement practice may build executive procedures within functions of sensorimotor coordination as part of the movement exploration rather than via a process of FA meditation. Finally, the domain of movement may provide not only an effective opportunity for improving the functional coordination of movements, goals and attention, but also yield cleanly operationalized measures of improvements in performance of the trained motor skill—thus being highly amenable to empiric study.

Our central hypothesis is thus that mindful movement practice may improve executive and attentional control by providing opportunities for learning functional coordinations of goals and attention, and that this might be productively modeled as *skill learning* (**Table 1**). Specifically, learners likely refine the flexible coordination of inhibitory and excitatory associations organized within learned action sequences or procedures. Much as in the practice of other motor skills, learned attentional or executive skills may initially be "declarative" or "cognitive," but with practice become proceduralized and ultimately automatized. At the neural level, we predict that this will—again, as with other motor skills—be reflected in rapid changes supported by subcortical structures, followed by consolidation at the cortical level (primarily in motor, prefrontal and posterior parietal regions), with a gradual decrease in prefrontal activation as attentional skill develops (Ungerleider et al., 2002; Robertson, 2009, provide neural accounts of motor skill learning) In a mature skill, functional procedures are automatically and efficiently engaged in appropriate contexts, which would also be observable as a gradual reduction in reaction times or reduction in error (Fitts and Posner, 1967; MacKay, 1982; Beilock and Carr, 2004). In the limit, however, "overlearned" skills become inflexible, and transfer to novel contexts is reduced (Karni et al., 1995; Bapi et al., 2006). While we propose multiple potential neural mechanisms below (all of which require further investigation), we also argue from a computational level that if gains from motor practice are to transfer to classroom behavior or laboratory tests of attentional control, then some part of what is learned must remain sufficiently abstract to apply across these various contexts. Formally, if higher-order skills are learned under conditions of variability and uncertainty, this may yield "structural" learning that facilitates sharing procedures across tasks. Following Marr (1982) this specification of a computational criterion—here, the

TABLE 1 | Attentional and cognitive control as coordinated sensorimotor processes.

Process	Characteristics	Sensorimotor influence	Discussion
Cognitive development (A-not-B error)	Goal fixation via persistent motor activity	Resolved by external inhibition of motor activity or by strengthening of sensation	**Section**: The Developmental Emergence of Cognitive Control in Reaching (Smith et al., 1999; Thelen et al., 2001; **Figure 1A**)
Mind wandering	Decoupling of intended goals (tasks) leading to wandering thoughts	Created by unintended goals or distracting sensations	**Section**: Mind Wandering, Focused Attention (FA) Meditation and the Body (Smallwood and Schooler, 2006; Christoff et al., 2009)
Beginning mindfulness via body sensation (body scan)	Decoupling of unintended goals leading to reduced rumination	Achieved by enhanced sensation of the body	**Section**: Mind Wandering, Focused Attention (FA) Meditation and the Body (Kerr et al., 2013)
Focused attention meditation practice	Process of volitional focusing on intended goal and decoupling from unintended goal	Achieved by learning efficient (re-) selection of intended goals via practice of cognitive control	**Section**: Mind Wandering, Focused Attention (FA) Meditation and the Body (Hasenkamp and Barsalou, 2012; Hasenkamp et al., 2012)
ADHD	Dysregulation of cortical mechanisms of inhibition and selection yielding inattention and impulsivity	Dysregulation plays out across cognitive and motor behavior; Mindful movement as a basis for improvement via learning procedural co-ordination of selection/inhibition	**Section**: Motor and Cognitive Control in ADHD (Mostofsky and Simmonds, 2008; Aron and Poldrack, 2005; further developed in this manuscript)
Mindful movement practice (e.g., Tai Chi Feldenkrais)	Skilled coordination of goals, sensations and motor/cognitive control within structural procedures	Achieved by learning abstract higher-level coordination skills via mindful learning (sensitivity to distinctions), fostered by the continuous and immediate sensorimotor feedback enacted in movement	**Section**: Mindful Movement Practice (developed in this manuscript; **Figures 1B**, **2**)
Inhibiting muscular contraction (ATM "lengthening the hamstrings")	Pattern of chronic habitual selection resulting in muscular contraction (shortening)	Resolved by an initially pre-conceptual mode of mindful sensation that derives coherent patterns of inhibition of habitual musclar contraction, which later establish co-ordination procedures via skill learning	**Section**: Coordinating Physical Movement: Inhibiting Muscular Contraction (Stephens et al., 2006; example ATM provided in **Supplementary Video 1**)
Coordinating attention: motoric mind wandering (ATM "flex hand to stand")	Decoupling from intended movement via absorption of control and attention in a secondary movement	(1) Sensing sensorimotor relations and goal deviations; (2) practice of goal-maintenance via initially cognitive co-ordination; (3) eventually establishing skilled goal-maintenance via procedural co-ordination of attention via skill learning; (4) continued practice over a large variety of movement contexts may lead to transferable skills for goal-maintenance	**Section**: Coordinating Attention: Motoric Mind Wandering as a Context for Practice (formally introduced in this manuscript; **Figure 1B**; stills of example ATM in **Figures 3A,B**, entire ATM in **Supplementary Video 2** and **Supplementary Video 3**).

structural learning of abstract, transferrable skills for attention and goal-based executive control—is a critically important (though often underdeveloped) component of our theory of attentional skill.

A Motor Perspective on Attention and Self-Regulation

Below, we present evidence from normal development and skill learning for a conception of attention and executive control emerging as coordinated activity across sensorimotor networks. We selectively review premotor theories of attention, which relate attention control to coordination via biased competition processes within movement planning. We then summarize integrative dynamical systems explanations of (impaired) cognitive control in Piaget's classical A-not-B error, which similarly relate competition processes in sensory and motor activity constitutively to cognitive content and goals. We finally apply the notion of control as sensorimotor competition to outline a sensorimotor theory of executive function for mind wandering and mindfulness.

In the section Motor and Cognitive Control in ADHD, we will apply our sensorimotor competition perspective on control to the co-occurring motor and cognitive control impairments observed in ADHD. In particular, we will incorporate evidence that points to a general dysregulation in mechanisms of inhibition and selection. In the final section Mindful Movement Practice, we provide some initial suggestions for applying and testing our hypotheses. The structure of proposed interventions are mainly drawn from the Feldenkrais method of mindful movement and Langer's mindful learning. We propose that mindful movement practices provide conditions for learning a skilled coordination of goals, attention and actions with specific transfer to challenges such as inhibiting unwanted actions or detecting mind wandering.

Attention is Closely Linked to Movement

Natural shifts of attention to a large degree occur through movement, in particular via overt whole-body movements of gaze including eye-, head and body (Land and Hayhoe, 2001; Schumann et al., 2008; 't Hart et al., 2009). On the one hand, attention can move automatically and transiently between places in the world via exogenous reflexive stimulus-driven processes, presumably to direct the sense organs to highly salient aspects and potential danger (Posner, 1980; Prinzmetal et al., 2005). On the other hand, as organisms with increasingly complex brains have evolved, their reactions have become increasingly dominated by "top-down" factors and a hierarchy of self-established internal goals and models (Fuster, 2001; Striedter, 2004; Einhäuser et al., 2008). Such endogenous overt shifts of attention are integral parts of higher-level motor control schemas that frequently pick up critical task information at anticipated points of action (Tatler et al., 2011). Further, following sensorimotor accounts on perception, endogenous attentional schemas are integral to perceptual phenomena such as viewing a scene *per se* (O'Regan and Noë, 2001), explaining for instance how a viewer's active sequential attentive engagement can render them unaware of major changes in the environment as demonstrated in inattentional blindness (Mack and Rock, 1998) and change blindness (Rensink et al., 1997; Simons and Rensink, 2005).

Recently proposed premotor theories of attention argue for a shared motor circuitry between overt and covert attention equating covert shifts of attention with goal-planning processes in the premotor system (i.e., movement of focus independent from movement of the sense organ). Laboratory tests of attention often entail covert shifts in attention (as opposed to overt shifts via gaze movements) that yield enhanced sensory acuity and reaction times, even for relatively simple tasks (Posner, 1980). Physiological evidence suggests that such covert attentional shifts engage the motor planning circuitry of saccades and may be thought of as planned saccades that are not (yet) executed. Thus, a "planning" state may selectively enhance processing at the attended location while raw sensory inputs remain largely unchanged (for a review, see Rizzolatti and Craighero, 2010). Moreover, these covert shifts are dominated by automatic, stimulus-driven (exogenous) processes at the shortest latencies, but over the course of 100 s of milliseconds become dominated by more abstract and integrative goals and predictions of expected results (Posner, 1980; Prinzmetal et al., 2005). This dynamic control of covert attention mirrors the time course over which sensorimotor coordination comes to be driven not only by immediate external information but also by internal goals, memories and integrated models (cf. Smith et al., 2006; Clark and Ivry, 2010). That is, overt movements and covert movements of attention appear to engage analogous "fast" and "slow" mechanisms, and moreover, the "slow" modulatory operations of executive goals and models occur over similar timescales. While not uncontroversial, even moderate accounts interpret the available data as a contribution of the motor system to a biased competition process underlying covert attention (Desimone and Duncan, 1995; Treue, 2001; Smith and Schenk, 2012) that is consistent with our proposed sensorimotor model of a shared neural basis for selection and inhibition in the control of overt movement, executive control, and control of attention.

The Developmental Emergence of Cognitive Control in Reaching

From an embodied sensorimotor perspective, any complex behavior depends on the interaction of multiple systems and behavioral difficulties may likewise arise or be addressed throughout these interacting systems (Wilson and Golonka, 2013). Smith et al. (1999) provide one such example of how carefully examining a task—here, the A-not-B error (Piaget, 1974) we might interpret a classic developmental "impairment" in cognitive control instead as the result of a dynamic sensorimotor process. As compared to traditional notions of cognitive concepts, an embodied view of shared dynamical systems leads to a novel set of non-conceptual interventions for an apparently conceptual deficit. Infants appear to gain stable representations for goal-directed movements (i.e., in the absence of an immediate perceptual stimulus) around 8- to 10-months of age—younger infants' motor systems are presumably too variable to support such goal representations (Spencer et al., 2006). Superficially, however, it appears that infants in this age range are unable to update their concept of the location of a desired toy. They reach for the old location A when a toy is moved under their sight to a new location B (though interestingly, only after a delay of a few seconds, thus allowing time for a visuo-spatial representation to decay).

An account that rests on a simple conceptual difficulty, however, is untenable as children at 7 months already demonstrate expectations of the correct location in looking time experiments. Smith et al. (1999) provide an alternative analysis, demonstrating that changing the motor plans required to reach for A and B locations—for instance by bringing the child to stand—eliminates the "erroneous" prepotent impulse to reach for the incorrect location A. Similarly, also enhancing infants' attention to their own arms—for instance with wrist weights, and gold lamé sleeves—eliminates reaches to the incorrect location A (Thelen et al., 2001). By contrast, increasing the complexity of the reaching movement can generate reaching to the incorrect location even in older children and establish analogous reach biases in adults (Wilson and Golonka, 2013). That is, through the alteration of possible motor plans, attention to sensations of the body, or the modulation of required effort, a seemingly "conceptual" and impenetrable difficulty can be either overcome or created.

Somewhat in line with the neural models of competitive goal selection discussed above (Fuster, 2001; Cisek and Kalaska, 2010), the action plan to reach for A may remain active (likely in premotor cortex), and signals (likely from prefrontal and posterior parietal cortex) regarding the new location are insufficient to inhibit the existing action plan and select a functional action plan prior to the initiation of a reach. Considering the reciprocal nature of the connections between motor and prefrontal cortex, Thelen et al. (2001) provide an integrative model in which dysregulated motor plans not only hinder the correct execution of the response, but are a constitutive part of the cognitive process in which mental events and bodily movement are "continuously meshed" (**Figure 1A**). In this embodied sensorimotor view, the motor interface can bias the entire sensorimotor network—including goals and attention—towards a coherent (but incorrect) representation, or "concept," of the desired object, providing a more complete explanation for the curious dynamics of the task, and the ability to correct the error from a variety of interventions in the infant's process of reaching. In a sensorimotor model, attentional and cognitive executive control processes such as selecting which location to attend and to reach are not localized in a modular structure, but emerge dynamically as a co-ordination process among shared resources within sensorimotor activity (cf. Barsalou et al., 2007). As a corollary, sensorimotor models predict that attention and executive control may be improved by sensorimotor interventions. From the onset of infants' interaction with the world, there is a role of movement in the enaction and development of robust, persistent concepts, i.e., the beginnings of cognitive control.

Mind Wandering, Focused Attention (FA) Meditation and the Body

A dysregulation of cognitive and attentional control that is common to all of us is the phenomenon of mind wandering. In contrast to the A-not-B error, mind wandering does not reflect a bias towards a given goal, but a deficiency to stay with a goal given a possibility for distraction. In mind wandering, the control of attention is said to decouple from an explicitly intended primary task, provoking deficits in both task performance and the accuracy of task-related perception. In line with models of control as emerging in the co-ordination of shared sensorimotor resources, mind wandering should not be viewed as a sudden "break down" of executive control, but rather as a goal-driven executive process in which other executive goals such as personal or organismic goals with higher reward become dominant—which may often be unintended or even implicit (Smallwood and Schooler, 2006). Such goals are thought to originate for instance in the default mode network (Christoff et al., 2009; Cosmelli, 2009; Hasenkamp et al., 2012), but from a sensorimotor perspective goals likely also result from motor plans that arise from affordances in the environment (Cisek and Kalaska, 2010).

Mindfulness, in comparison, may be seen as the successful, functional deployment of attention within a task or activity (extending Smallwood and Schooler, 2006). One of the more common (and most widely-studied) mindfulness practices to focus a wandering mind is FA meditation. In FA meditation, a central aim is the maintenance of attention on a specified target (e.g., the breath) in the context of unintended goals that may attract one's attention (i.e., distractions). The effects of FA meditation are increasingly understood, as is the characterization of neural correlates (Lutz et al., 2007; Kerr et al., 2013; Goyal et al., 2014; Lippelt et al., 2014), though there is a clear need for additional randomized trials (Allen et al., 2012).

Recent event-related paradigms have attempted to isolate distinct functional sub-phases in the dynamics of FA meditation (Hasenkamp et al., 2012). The first proposed phase of focusing attention meditation is *becoming aware* of the wanderings of the mind, which is an aspect of *sensation* with correlated activity in the salience network. This network is involved in error detection mechanisms in particular within interoceptive and somatosensory signals. A second phase, *shifting attention* back to the intended goal, involves lateral prefrontal cortex and lateral inferior parietal cortex areas of a task-positive executive network, highlighting that attentional disengagement, inhibition, is an aspect of reorienting. A final subphase, sustained *focusing* on the target, has been linked to "active rehearsal" in task-positive executive networks, potentially involving maintenance of the goal in working memory (D'Esposito, 2007; in Hasenkamp et al., 2012).

In line with our model of shared sensorimotor resources in attention and cognitive control, it has been suggested that the first phase of FA meditation—sensation—may be one reason why many meditative practices start by directing attention to the body. Changes in somatosensation (even those driven by shifting attention in the process of "actively" sitting still) may be easier to detect than wanderings of abstract thought. Mindful direction of attention toward or away from sensation in the hand leads to enhanced ability to modulate alpha activity in somatosensory cortex, and may actively bias thoughts away from rumination and towards the present—much as cognitive fixation in the A-not-B error is addressed by enhanced salience of sensory stimuli (cf. Kerr et al., 2013). A sensorimotor context may thus provide greater salience and clarity for the learner in situations where the basic mechanisms of selection and inhibition are dysregulated, as in ADHD.

A Model for Skilled Cognitive and Behavioral Control

We suggest that attentional training in mindful movement practices such as Tai Chi or Feldenkrais' Awareness-Through-Movement (ATM; described in the section Mindful Movement Practice) provides multiple additional opportunities for sensation as compared to the process of attending to the body at rest as in a "body scan." Most importantly, movement reliably *generates* concretely observable *changes* in body sensations for both the practitioner and the teacher, thereby providing concrete, differentiated, immediate and continuous feedback about the processes. Further, the control of movement also generates "feed-forward" predictions of sensory consequences (Wolpert et al., 2011) that allow a concrete sensory comparison between the expected and the actual sensations resulting from the movement that are used in error-based or predictive motor learning processes that are dependent on prefrontal cortex and the cerebellum (Blakemore et al., 2001; Shadmehr et al., 2010; Alexander and Brown, 2011). While clearly not all motor learning signals are penetrable to consciousness, the degree of conscious penetrability of both types of sensorimotor signals has been related to awareness and abnormalities in the sensation of the body (Blakemore et al., 2002). In a movement practice, the processing of these signals

TABLE 2 | Modes of skill learning (adapted from Wulf, 2007).

Mode	Features of movements
Conceptual mode	Movements are slow, inconsistent, and inefficient (awkward). Considerable higher-order activity, fragile under distraction. Possibility to develop novel associations and procedures.
Associative mode (transferrable structures, abstract representations)	Flexible application of learned associations and procedures.
Autonomous mode (motor coding, not directly accessible to consciousness)	Fast, efficient execution in learned contexts (decreasing transfer). Attention can make performance worse (cf. Choking).

These "modes" are often presented as "phases." The switch in terminology is meant to suggest that this may not be a strict or one-way progression.

may be modified by attentional focus, and the practitioner may also become aware by distinguishing sensorimotor sensations via mindful *comparison* (Feldenkrais, 1972; cf. Langer, 2000) between expected and unexpected sensations accompanying her actual movement, leading to a refinement of coordination and body awareness (**Figure 1B**).

If beyond sensation during movement, we further consider mindfulness training within the classic three-stage motor skill learning model proposed by (Fitts and Posner, 1967; **Table 2**), all three sub-phases in the above description of meditative mindfulness via FA are reminiscent of the first "declarative" or "conceptual" stage of classical (motor) skill learning. In this phase, enhancing sensation by attending to the body may provide clearer feedback signals during trial and error learning. Once trial and error learning has established a sufficient procedural repertoire for the task, however, skill learning enters a second "associative" phase in which the new repertoire is practiced and refined until the sensorimotor associations gain robustness to interference. Frequently distracting aspects become associated with the underlying goals and are directly inhibited as part of the skillful selection of appropriate procedures, until in a last autonomic phase, no apparent interference can be observed (Fitts and Posner, 1967). Continued attention to sensory experiences of the present movement during these later phases of practice may enhance the selection, refinement, and increasing automaticity of initial sensorimotor associations. Specifically, learned procedural knowledge about that task may allow attention to better distinguish errors and distraction from task-relevant features, including strategies for transfer and adaptation to novel contexts (Langer, 2000).

Consistent with an associative learning of procedures in later stages of skill learning, experienced meditators show less activity in motor related areas (including SMA and cerebellum) during the shifting phase, implying more efficient neural inhibition and selection, along with an increase in resting-state connectivity within the executive network (including dorsolateral prefrontal cortices) that is implied in attentional disengagement and inhibition (Hasenkamp and Barsalou, 2012; Hasenkamp et al., 2012). Similar decreases in the engagement of attentional networks have been observed in experienced meditators (Brefczynski-Lewis et al., 2007). This pattern of results may indicate a practice effect in a *generic capacity* for disengagement in which a well-learned shifting requires less neuronal activity—for example via generic enhanced prefrontal and premotor connectivity, along with subcortical structures, for example in the cerebellum (Hasenkamp and Barsalou, 2012). However, in the motor learning literature, it has been suggested that spontaneous resting state activity following the practice of a skill is influenced in specific ways related to *functional activity* in the practice of the skill, contributing to the consolidation of procedural memory (Miall and Robertson, 2006; Albert et al., 2009; Taubert et al., 2011; Vahdat et al., 2011). Hence, from a skill perspective, resting state connectivity increases following FA meditation training may also be explainable by *procedure-specific* connectivity that encodes an elaborated *repertoire* of task-relevant contingencies between goals, the required actions, and the accompanying sensations (e.g., mindfulness of how to exploit the available degrees of freedom to maintain breathing while organizing complex actions with the body). In the motor domain, learning would comprise an elaborated set of possible actions more finely-discriminated to sensory contexts that give rise to the motor skill. Importantly, structural, abstract procedural representations may transfer between the learning contexts and contexts with a similar structure (Braun et al., 2009; Shadmehr et al., 2010; Wu et al., 2014). We propose that mindful movement training could similarly yield an enhanced repertoire of *attentional contingencies* (that, for example, allow one to maintain attention amidst distractions) and indeed, a structural sensorimotor repertoire (per Braun et al., 2009) may directly underlie aspects of skillful control of attention.

Both capacity and procedural theories suggest alternative, testable predictions for gains in attentional skill. On the capacity account, one would expect broad similarity across tasks that require efficient operation of trained networks—for example *any* motor behavior or control of attention featuring prefrontal motor and premotor cortices. Over the course of skill acquisition, one would expect a general reduction, for example, in prefrontal activity as efficiency increased. On the procedural account, however, one would expect a larger role of task specifics, in which transfer to novel (but related) activities may require additional variational training and structural sensorimotor representations or internally generated "contexts" (e.g., specific mental states). In this case, well-learned structures or contexts might yield less activity throughout prefrontal and motor networks, while structurally novel tasks elicited greater activity.

In summary, multiple lines of evidence support our consideration of attention and control in the context of motor skill learning. Below, we will see that local inhibitory mechanisms within motor cortex are diminished in ADHD, suggesting an impairment that spans the hierarchy of neural selection and inhibition elaborated above (cf. Fuster, 2001; Cisek and Kalaska, 2010). Indeed, Thelen et al. (2001) demonstrate how the activation of motor plans appears to modulate cognitive flexibility in the A-not-B error. Hence, multiple brain regions and cognitive capacities are likely relevant even in basic cognitive tasks via *reciprocal* inhibition and selection. Smallwood and Schooler (2006) suggest that even "undesired" shifts of attention may be considered not so much as away from an intended focus, but rather as shifts *towards* novel executive goals that may be either explicit but also implicit. While such shifts may be counteracted via effortful, executive processes of selection and inhibition, we suggest that in skillful performance, goals, motor plans, and attention will flow more automatically within well-learned and well-structured functional procedures that entail knowledge of how to maintain attention and goals under distractions. Hence, we suggest that while a generic capacity model may explain improvements in attention, a skill-based model in which specific associations are strengthened in the context of functional procedures is a compelling alternative model. This unified model comprises neural processes across basic motor actions and high-level cognitive skills as well as functional skill learning principles, suggesting a profound potential for successful improvements in cognitive function via mindful movement practice (**Table 1**).

Motor and Cognitive Control in ADHD

The first empirical test of our theory is currently underway, in which we are applying a battery of motoric and cognitive assessments to children with ADHD before, during and after a mindful movement practice (in this case, tai chi). ADHD is clinically relevant and also provides an interesting mirror for the difficulties encountered in FA meditation (Zylowska et al., 2009). Consider the difficulties that beginning meditators have with mind wandering—maintaining an attentional focus that wanders on its own—and also with sitting still. For most, sustaining FA and sitting still does not occur without effort—specifically effortful inhibition of movements or attentional shifts (cf. Kahneman, 1973), and when this fails, effortful re-selection of the desired state. As elaborated above, most individuals appear to have difficulties maintaining an ideal balance between goals that serve one's long-term interests vs. goals triggered by novel or immediately attractive stimuli. One could characterize the challenges in ADHD as difficulty with sustaining a task with little immediate reward, or with resisting a novel impulse (Aron and Poldrack, 2005). These difficulties might be addressed by enhancing one's ability to sustain engagement in "important" tasks (e.g., tasks with substantial long-term rewards).

Following our treatment of mind wandering above, we likewise propose that ADHD symptoms my result from dysregulated inhibition and selection within a network of sensations, goals and motor plans. This dysregulation might make it particularly difficult to learn functional attentional associations and procedures (in addition to analogous behavioral difficulties). As such, motor practice that automatically elicits mechanisms of selection and inhibition may be more accessible to this population than more effortful and difficult practices. Features of ADHD may further elucidate relationships between cognitive inhibition and behavioral inhibition, which are difficult to observe in the general population (Kipp, 2005), potentially informing effective skill training approaches for improving cognitive skills for ADHD and in the broader population.

The Significance of ADHD: Motor Control, Attention, and Cognitive Control

Attention deficit hyperactivity disorder (ADHD) is the most common childhood behavioral diagnosis, affecting 3% to 6% of children throughout the world (Tannock, 1998; Brown et al., 2001). For a child with an ADHD diagnosis, significantly worse educational, social, and occupational outcomes are predicted (Mannuzza et al., 2008), as are higher medical costs in childhood (Ray et al., 2006). It is well-known that these children exhibit difficulties in cognitive and emotional regulation (Hinshaw, 2003; Cuffe et al., 2005). As we will see below, however, there are also clear motor control abnormalities that are well-correlated with the diagnostic features of ADHD. These motoric abnormalities may be central to our understanding and treatment for this diagnosis.

The NIMH maintains "Research Domain Criteria" (RDoC) for diagnosis and treatment in mental health contexts. This RDoC approach consists of a set of cognitive domains, with the goal of linking laboratory cognitive science with research and innovation in treatments (Cuthbert and Insel, 2013). In the case of ADHD, difficulties with response inhibition and selection are highlighted in the central capacities of attentional and cognitive control (often subsumed under the term "executive function; Aron and Poldrack, 2005; Mostofsky and Simmonds, 2008). Interestingly, these measures are similarly predictive of life outcomes in the broader population, including school performance, income, and mortality (Diamond et al., 2007; Moffitt et al., 2011).

ADHD is generally treated as a cognitive problem, but the poor outcomes that persist even after intensive treatment argue that other perspectives may be warranted (in particular, movement-based approaches may provide a particularly useful perspective). Cognitive evaluations of both psychotherapeutic and pharmacologic treatments primarily assess patients' executive abilities to maintain attention in the presence of distractions, to organize tasks, to inhibit impulsive responses to emotionally salient environmental stimuli, and to prioritize goals in response to reward. The most comprehensive NIH funded study of treatment of ADHD to date is the multimodal treatment of ADHD study (MTA Cooperative Group, 2004). In this 4-arm treatment study, children in the active 3 treatment arms received care that far surpasses in intensity the treatment routinely provided in the community (the active comparator arm). Short-term reductions in core ADHD symptoms were observed with psychostimulants, behavioral treatments, and a combination of both. Despite this, and surprisingly, at 8-year follow up, individuals in all treatment arms showed the same high rates of psychiatric hospitalizations, traffic citations, illicit drug use, and arrests. The poor long-term outcome of current therapies highlights the potential impact of novel treatments.

Motor Impairment is a Core Feature of ADHD

The co-morbidity of motoric and cognitive difficulties in ADHD point towards shared mechanisms and skills that may underlie correlations in these measures. Thus, while motor features of the disorder may not have as much direct impact on quality of life, they may clarify core features of ADHD, and in particular lead to refinements in movement-based practices with already-demonstrated benefits (Hernandez-Reif et al., 2001; Jensen and Kenny, 2004; Balasubramaniam et al., 2013; Converse et al., 2014).

Overt Motor Behavior in ADHD

It has long been observed that children with ADHD demonstrate impairments in motor control that parallel impairments in cognitive and behavioral control (Denckla and Rudel, 1978; Kadesjö and Gillberg, 1998; Piek et al., 1999). Studies consistently reveal extremely high rates (50% and above) of comorbid Developmental Coordination Disorder (DCD) in children with ADHD (Kadesjö and Gillberg, 2001), in particular, impairments in motor inhibition and selection correlate with the deficits in attention and cognitive control that define the disorder (Gilbert et al., 2011; MacNeil et al., 2011), and measures of automatic and intentional motor inhibition are likewise correlated (Mostofsky et al., 2003). In studies of specific overt motor signs, investigators have consistently found children with ADHD show excessive motor overflow (Denckla and Rudel, 1978; Szatmari and Taylor, 1984; Waber et al., 1985; Mostofsky et al., 2003; Cole et al., 2008; MacNeil et al., 2011), and impaired motor response control (Mostofsky et al., 2003; Mahone et al., 2006), as well as general findings of impaired motor coordination (Denckla and Rudel, 1978; Piek et al., 1999; Kadesjö and Gillberg, 2001; Mostofsky et al., 2003; Cole et al., 2008). Children with ADHD also demonstrate motor impersistence reflective of broader impairments in maintaining on-task behavior (Mahone et al., 2006).

In an attempt to understand the core features of these motor irregularities, we consider here the relatively automatic phenomenon of motor overflow, for instance mirror overflow movements. In typical development, *mirror movements* are observed, as in unintended movements in the left hand when intentionally moving the right. This overflow can be elicited in controlled laboratory settings, and will diminish as a child's capacity for motor inhibition (and with that, selection) improves during development. Even as adults we may experience occasional mirror overflow (e.g., activity in the lips or hands), as when focusing intently on a precise task. Elevated overflow is revealed consistently in children with ADHD across a range of studies using a variety of methodologies to quantify motor overflow movements (Mostofsky et al., 2003; Cole et al., 2008; MacNeil et al., 2011). Furthermore, among children with ADHD, increased levels of motor overflow correlate with measures of impaired cognitive control (Mostofsky et al., 2003).

Neurologic Irregularities in ADHD

Multiple lines of research have clarified a brain network of regions spanning basic motor control, higher-level executive and subcortical structures that are implicated in response inhibition, and to some extent, in the pathophysiology of ADHD. The unifying feature of this network appears to be participation in the inhibition and selection of behaviors—ranging from simple movements to abstract, higher-order procedures. The right Inferior Frontal Cortex (IFC), for example, appears to be central to behavioral control in the Go/No-go and Stop-signal tasks, and moreover has a reduced volume in ADHD (Aron and Poldrack, 2005). The Supplementary Motor Complex (SMC; in particular the most rostral aspect, the pre-SMA) additionally plays a central role in response preparation, selection, and execution and exhibits decreased volume in ADHD. This role of the pre-SMA is unlikely to be a mere downstream effect of prefrontal activity, as Isoda and Hikosaka (2007) demonstrate facilitation of response switching via direct stimulation of pre-SMA in rhesus monkeys. Some neurons within this region were found to be specifically responsive to cues signifying "go" (selection/initiation), while others selectively responded to "no-go" cues (inhibition). Cisek and Kalaska (2010) likewise summarize electrophysiological findings pointing to dorsal premotor cortex as a primary locus of action selection under natural conditions, and this region is again reduced in volume in ADHD (Mostofsky and Simmonds, 2008). Thus, it seems that individuals with ADHD have pervasive neurologic deficits relevant to behavioral control that span basic sensorimotor associations, coordination of multiple competing motor plans, and higher-level inhibition and selection (see Mostofsky and Simmonds, 2008, for an overview).

Neural correlates of impaired response inhibition in ADHD have also been observed with basic and unconscious control of actions generated at the level of primary motor cortex (M1) via the phenomenon of *Short Interval Intra-Cortical Inhibition* (SICI; Kujirai et al., 1993), a modulation of the electromyographic (EMG) activity that would normally be elicited by a TMS pulse over M1. The SICI phenomenon is obtained by applying a conditioning pulse followed by a second "paired" pulse delivered 3 msec later, and this second pulse will elicit reduced EMG activity compared to a single-pulse baseline. This mechanism is understood to be the result of GABAergic motor inhibition in the local network. As described above, children with ADHD exhibit decreased inhibitory control of movement, and this is further reflected in the observation that SICI is also significantly reduced in children with ADHD. Importantly, this reduced SICI (higher ratios) robustly correlates with ADHD symptom severity (measured using the Conners teacher survey). Further strengthening this linkage, psychopharmaca for cognitive symptoms address motor symptoms as well: two studies of stimulant (methylphenidate) effects on SICI revealed enhanced inhibition of approximately 10% and 20%, respectively (Moll et al., 2000; Buchmann et al., 2007).

Treating ADHD

As discussed above, poor long-term outcomes are observed in ADHD even with intensive treatment. If the difficulties in ADHD are indeed based on a need to develop *skills*, this would be unsurprising – there is likewise no pill or conversation that can lead to the skill required to ride a bike. The behavioral, imaging, and electrophysiologic evidence reviewed above indicate that ADHD is associated with impairments in control of not only complex executive functions, but also basic motor actions. Parallel, and even correlated, impairments in inhibitory control are observed across motor, premotor and prefrontal systems. These structural and functional neuromotor irregularities in children with ADHD point not only to an explanation for dysregulated movement, but more generally to dysregulated mechanisms of inhibition and selection that may similarly underlie difficulties with both learning and performance of cognitive skills like the context-appropriate maintenance of attention. These findings are consistent with our model developed above (**Table 1**, section A Model for Skilled Cognitive and Behavioral Control) in which inhibition and selection of executive goals or attentional focus are an intrinsic part of the motor skill repertoire. While our model demands further validation, below we review current data indicating that movement training may provide an opportunity to practice and improve skills that are deficient in ADHD, potentially providing similar benefits to the general population (as in the case of mind-wandering).

Mindful Movement Practice

As discussed below, movement instruction provides a context—by verbal instruction, guidance via touch or physical environment—which helps the participant to explore and perceive functional sensorimotor relations in more detail and from different perspectives. Movement itself continuously provides concrete, immediate and differentiated feedback about the process of practice (**Figure 1B**). In this feedback, a student, for example, can observe "invariance, i.e., different ways of moving that produce or prevent a certain outcome. Gains in attentional, executive, and behavioral control have been observed in adults engaged in mindful movement training, such as tai chi (Miller and Taylor-Piliae, 2014; Wayne et al., 2014; Wei et al., 2014), yoga (Balasubramaniam et al., 2013; Gard et al., 2014b), and dance (Kattenstroth et al., 2013). Improvements in cognitive control symptoms for young adult and pediatric ADHD populations have also been observed with tai chi (Hernandez-Reif et al., 2001; Converse et al., 2014) and also Yoga (Jensen and Kenny, 2004). These results should be interpreted with caution, as none of the interventions for cited for ADHD were randomized trials (though reviews above do include such trials). Likewise, body-based mindfulness training in children has yielded teacher-reported gains in attention and concentration in 4th and 7th graders, and improvements on the flanker task in preschoolers (Zelazo and Lyons, 2012).

Following our model of skilled control of attention, our central hypothesis is that long-term practice of *mindful* movement may train the ability to continuously monitor movement, register deviations and update structural motor procedures that guide or maintain attention within movement. Much as with the accounts of skill learning and FA meditation described above, such continuous monitoring will likely initially yield enhanced prefrontal and premotor activity as novel coordinations are learned and competing motor programs are resolved. Appropriate practice may lead to increased mindfulness (or awareness) when a skilled deployment of attention reaches the autonomous and automatic phase described in skill learning models in the motor domain. At this stage, overall differences in, e.g., fMRI signal from a naïve baseline may be difficult to detect (for example, enhanced prefrontal activity during behavioral or attentional control may drop with automatization). However, we would expect that more robust neural selection and inhibition may be detectable via measures such as TMS SICI (which is deficient in ADHD, as described in section Neurologic Irregularities in ADHD). Overall, it will be critical to assess the effects of mindful movement training throughout the timecourse of learning, using both behavioral and neural measures.

Feldenkrais (1947) was among the first to articulate an argument *founded in neural information processing* that a general skill of awareness and improved behavioral control can be developed via mindful movement training. Feldenkrais developed his movement practice in dialog with a number of leading neuroscientists of his time, such that his theoretical model is informed by basic neuroscientific principles from the historical context ranging from the 1950's to the 1970's. His approach was also informed by his extensive first-person experience in movement, in particular as a Judo master (Feldenkrais, 2010). A particularly clear definition of Feldenkrais' conception of "awareness" (his preferred term for mindfulness) was stated as "a process of full concentration, a process of clear analytic action on the points you deal with at that particular moment... involving a real use of an operational procedure" (Feldenkrais, 2010, 165). This conception is consistent with our model that situates attention and executive function within refined sensorimotor associations and procedures. Feldenkrais' movement lessons, termed "Awareness Through Movement,"[1] or ATM (Feldenkrais, 1947, 1972, 1981; Sheets-Johnstone, 1979; Buchanan, 2012) provide the nervous system with *information* about coordinating the body during action. During the complexities of human body movement, higher-level motor control provides an integrative mechanism of sensorimotor planning, error detection and decision-making. The critical role of mindfulness in learning and training—particularly for transfer—has since been discussed even in the development of abstract skills, such as computer programming (Salomon and Globerson, 1987; Langer, 2000). Admittedly, however, evidence for the efficacy of ATM is currently provisional (Buchanan,

[1]What is today know as the Feldenkrais Method consists of movement lessons conducted with groups by verbal instructions for movement, called "Awareness Through Movement," as well as individual hands-on explorations including manual touch called "Functional Integration." We focus on the verbal movement instruction approach within this paper.

2012; Hillier and Worley, 2015).[2] Thus, we primarily take the ideas of Feldenkrais (and also others) as a starting point for our model of mindful movement. We nonetheless propose that mindfulness may be a powerful tool for structural learning that yields transferrable, higher-order procedures, and that movement is an efficient and convenient domain for such training.

Mindful Motor Skill Practice

Langer notes that "[b]eing mindful is the simple act of drawing novel distinctions. It leads us to greater sensitivity to context and perspective, and ultimately to greater control over our lives" (Langer, 2000, 220). Langer's (2000) experiments suggest that this ability to sense discriminations allows for a mode of mindfulness grounded in flexible application of what is learned to the present situation or domain. When relevant distinctions go unnoticed, we are instead influenced by habitual responses and impulses that do not match the situation. A "mindless" state can thus result from a fixed and inflexible set of behavioral rules and factual knowledge that are inappropriate to the current task, or in other words, mindlessness may result from *inappropriate* mental focus. Conversely, drawing novel discriminations while being attentive to context, to variation and to perspective during learning appears to establish a mindset that is attentive to possible differences, leading to mindful awareness. In the context of our skill learning model, this mindset may prohibit overlearning—using contextual variation to force a level of abstraction in what is learned that is necessary for effective transfer to novel domains. How one learns seems as important as what one learns (Langer, 2000).

Feldenkrais argued that if the mind is grounded in the control of movement, learning to improve the quality of movement is an effective way of acquiring or developing general principles of learning. In particular, he made use of sensory discrimination for becoming aware of different ways of sensorimotor *actions* (for instance the movements involved in breathing freely, or in maintaining posture in gravity against a support surface, in turning the head or the body for orientation) in a form of learning that "... leads to new and different ways of doing things [one] already knows how to do [such as breathing or turning]. This kind of learning increases [one's] ability to choose more freely. Having only a single mode of action means [one's] choice is limited to simply acting or not acting" (Feldenkrais, 1981, 35). While ATM lessons are practiced in movements, Feldenkrais argued that improvement in how one "directs oneself" while moving—cognitive control—is more important than the actual movement that is performed (Feldenkrais, 1981, 36). Hence a primary goal of his approach is that students may use the medium of movement for learning to direct their goals and attention, ultimately leading to better skills for "learning to learn" (i.e., for mindful learning), and not merely the ability to maintain FA.

Guiding Awareness to Sensory Details

Feldenkrais worked from the supposition that movement coordination can be improved by providing relevant *sensory* information to the nervous system that differentiates functional components of action, either within the body (such as kinematic links between body parts), to the world (such as kinematic links to support surfaces), or within the central nervous system (e.g., the scope of the available repertoire of motor procedures). Two main assumptions are that movement organization is (partially) constituted by structural sensorimotor knowledge (e.g., the movements in which a force in standing or walking travels from the feet through the body), and that individuals can sense novel functional differentiations of these relations, leading to a more effective organization of actions. Both assumptions are in line with theoretical work on motor learning (Bernstein, 1996; Körding and Wolpert, 2006; Connors et al., 2010; Wolpert et al., 2011). First neuronal evidence is found in an fMRI study of a sensorimotor manipulation based on Feldenkrais principles. Here, an attempt to differentiate possible relations of the feet to the body engaged action-related neural processes, accompanied by the subjective experience of naïve participants of an "easier", "more controlled" usage of the leg in pushing or standing, and being "more stable, better able to keep balance" (Verrel et al., 2015).

ATM lessons attempt to guide students to notice subtle distinctions between movements, a process which is aided by instructing the use of slow, small-magnitude movements performed under minimal effort. Lessons often begin in a supine position on the floor so that movement sensations can be experienced with minimal muscular tone and associated anti-gravity control patterns that are engaged in standing. Reduction of muscular effort, following a fundamental psychophysical principle in which reduction in total sensation results in smaller "Just Noticeable Differences" (as developed by Weber and Fechner; Murray, 1993), improves the thresholds of kinesthetic sensations and hence their acuity. For this reason, one cross-cutting "learning to learn" aim of ATM lessons is to develop students' procedural knowledge of how to reduce the overall effort in action in general to allow finer distinctions in sensation (Feldenkrais, 1972). This is achieved for instance by the instruction to sense the onset of effort in a movement, e.g., lifting the shoulder, and then to reduce the extension of the movement to a range where it can be performed without effort, or by the instruction to sense secondary signals such as contractions or relaxation of the face or jaw that are often accompanied with effort as a feedback signal to distinguish effortful and effortless ways of moving.

Verbal instructions regarding the direction of attention during these movements aid in distinguishing useful components of action (e.g., widening of the chest in multiple directions while breathing) from often unnoticed habitual components (e.g., habitual raising of the right shoulder with each inhale) that do not serve the movement task one intended (though these

[2] We are currently working with practitioners to make unpublished materials available. One such example is provided in the **Supplementary Video 4**. There, range of movement videos are taken before and after a one-week Feldenkrais intervention. An illustrative frame from **Video 4** is provided in **Figure 3C**.

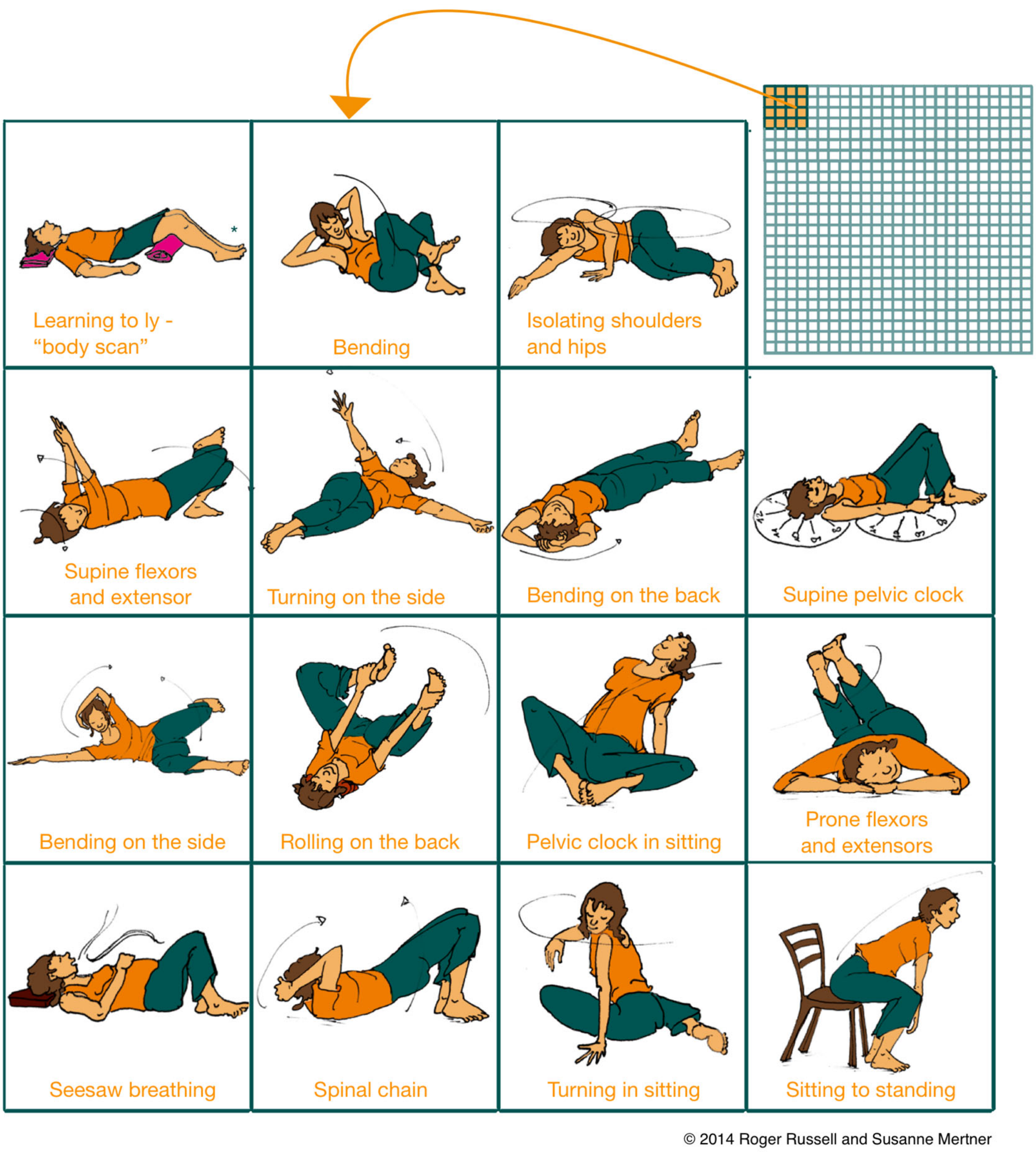

FIGURE 2 | Mindful movement practices afford a large variability of tasks and engage in active, exploratory learning. Movement variability and exploration induces structural learning of what is common between two tasks (such as between cycling and motor cycling or between different movement lessons). Structural generalization of skills skills fosters transfer to novel domains. Depicted is a small subset of starting positions of the over 600 classical ATM lessons (matrix in the upper right corner) developed by Feldenkrais, exploring different movement themes over a broad variety of movement contexts. Similarly large numbers of structural movement variations are provided by traditional practices such as tai chi. Figure adapted with permission from Russell (2014).

habits would likely have functional use in other movements, here e.g. for breathing while reaching with the arm).

Many disciplines include attentional instructions, for example to attend to the breath, or to focus on remaining balanced. The instructions in an ATM lesson direct attention to sensorimotor features in a broader variety of specific processes with a clearly describable target (e.g., attending to a particular movement of the head), though the details of the attended target may be difficult to convey in verbal language given the large number of degrees of freedom in the body. Similar difficulties are observed when asking an observer verbally about specific features of multidimensional stimuli in psychophysics (Ehrenstein and Ehrenstein, 1999). ATM lessons apply the psychophysical method of comparison, in which critical features are rendered salient in sensation via *comparison* between two stimuli, to mindful practice. Verbal attention instructions in ATM often prompt for directing attention directly within the sensorimotor space by comparisons between concrete sensations (for instance asking the student to observe changes in the contact areas of both shoulders to the floor between the left and right side to notice the precise onset where each shoulder begins to contribute to a rolling movement the head). Here, the overall goal is that students gain the ability to actively utilize the continuous, direct and differentiated feedback generated in movement to sense specific components of their own idiosyncratic way of acting, training an attentional skill.

Finding and Refining Novel Procedures

Central to sensorimotor skill learning and mindful learning is that the student directly evaluates and explores new ideas or movement organizations (Held and Hein, 1963; Langer, 2000; Lotze et al., 2003; Berthouze and Goldfield, 2008; Iftime-Nielsen et al., 2012). A repertoire of associations, procedures and concepts is likely defined by the developmental genesis of a sensorimotor repertoire that includes the coordination of attention and goals (see, for example, Smith and Thelen, 2003; Spencer et al., 2006; Barsalou et al., 2007). We hypothesize that ATM scaffolds active reorganization of this repertoire along with the development of novel movement components, including movements of attention, via challenging "movement puzzles" which are difficult to "solve" based on habitual movement and habitual skills alone. ATM movement puzzles provide hard biomechanical constraints that can *force* attentive exploration across a lesson. For instance, the lesson "Coordinating Flexor and Extensor Muscles" instructs students to move their torso to both sides while lying on the back with both feet standing, raising both arms in front to the ceiling above the eyes, palms touching as in clapping. In this position, the arms form a triangle that limits moving the hands to one side via the shoulder and thus encourages movement of the whole torso (Feldenkrais, 1972). The student is thus encouraged to intentionally explore automatic responses in comparison to novel coordinations, generating awareness of what he is doing habitually, of alternatives, and choice.

Importantly, mindful learning in both movement and cognitive tasks is distinct from rote repetition or single exposures, and it occurs naturally in learning conditions that include uncertainty and variability (Langer, 2000). Catalogs of Feldenkrais lessons include over 600 examples, each containing many variations on a movement theme, so that a huge variety of movements are explored with continuing practice (**Figure 2**). These lessons may explore the same biomechanical relationships (e.g., the role of the flexor and extensor muscles in movements of the torso) in various positions (e.g., lying on the floor, sitting, standing) or tasks (e.g., reaching, orienting or walking). Once a functional relation can be differentiated in sensation and action, the student practices flexibly applying their novel coordination repertoire in new functional contexts (i.e., new movement variations), thus "integrating" movement components across procedures and perhaps facilitating transfer to novel domains. Importantly, lessons may also explore the application of higher-level features of movement, including the coordination of attention and goals, which may be applicable to more purely cognitive tasks (as discussed in the section Coordinating Attention: Motoric Mind Wandering as a Context For Practice). In particular, once novel alternatives are found, Feldenkrais noted that students must invest conscious mental effort at the level of continuing practice if they wish to transform the novel movements into a novel habit, i.e., novel procedural skills (Feldenkrais, 1972, 60).

The reduction of effort, however, aids the exploration of novel alternatives. Feldenkrais proposed that movement under heavy load self-stabilizes the activation of the concurrent motor programs in an attempt to control strong forces of the movement (Feldenkrais, 1972). Conversely, slow and small amplitude movements may reduce the activation strength of existing motor programs and thereby foster the ability to sense and explore novel alternatives as well as to inhibit habitual components. In more advanced stages, students are asked to attend particularly to the initiation phase of the movement, for instance by asking what the earliest point in time is when the beginning of a movement pattern can be sensed—and potentially even motor initiation in the imagination of movement can be sensed. Aiding the emergence of novel patterns by reducing the activation strength of current patterns is similar to the above resolution of the A-not-B error (Thelen et al., 2001) in which changing the strength of over-dominant motor programs can allow for contextually integrated solutions to emerge. Similarly, this principle may explain (in part) Langer's (2000) observation that effortful implementation of a pre-existing solution may hinder learning of alternatives.

It is worth pointing out the central value of exploring with variability and effort reduction over practice by repetition within theories of motor learning. Bernstein noted that effective sensorimotor training would combine reduced effort with a large variability in the sensations (Bernstein, 1996), ideally leading to "dexterity" Bernstein's term for the ability to apply motor skills in novel situations. A breakdown in this ability to transfer even very basic skills was observed in a sequence learning task on a five-button keyboard, in which intermanual transfer is evident after 1 h of practice, but little to no intermanual transfer is found after 5 weeks of training (Karni et al., 1995). Thus, extended rote practice may tie a skill to a particular mode of execution. The absence of transfer suggests that participants failed to develop or maintain more abstract levels of representation.

We propose that mindful learning may operate (in part) by favoring abstract, transferrable procedures that include not only motor plans, but also the coordination of attention and goals. More recent approaches, for instance using reinforcement learning, demonstrate that movement variability aids motor learning by encouraging exploration (finding novel alternatives) rather than exploitation (applying known procedures) of the motor command space (Herzfeld and Shadmehr, 2014; Wu et al., 2014). Task variation allows learners to observe and learn a common structure in the co-variation of control parameters between two tasks. Learning such general functional structures rather than surface similarity yields a low-dimensional and task-general control parameter space that is shared between tasks, and hence facilitate transfer of skills to novel situations (Braun et al., 2009), and we propose this computational principle is likely to apply to the learning of attentional skills as well, in particular if developed during action.

Inhibition of Habitual Responses

A classically observed aspect important to mindfulness is the ability of withholding or inhibiting the first salient response (analogous to a stop signal task), thus providing the opportunity to select more contextually appropriate perspective or response to the present situation (Salomon and Globerson, 1987). When enacting an overt movement, in contrast to observing movements of thoughts, habitual movements are objectively observable via the immediate sensorimotor consequences even if the initial impulse is outside of awareness. Movement puzzles in ATM render habitual movement salient for awareness and open a window for inhibition. For instance, lifting one shoulder when lying on the back often habitually tonifies one side of the neck leading to a turning of the head in one direction, which may interfere with the ability to move the head independently from the shoulder. This habitual tendency can be detected and inhibited in movement exploration. However, Feldenkrais observed that becoming aware of the existence of a habit is likely not sufficient to reliably inhibit a habit when it is triggered, as some (or all) of the habitual process is likely *pre-conscious* (perhaps more akin to a developmental rather than a skill learning process). Thus, ATM lessons frequently instruct the student to intentionally perform a movement that is normally habitual in order to achieve some level of volitional control over the habit. One of the simplest examples we are able to provide is the lengthening of a habitually (or chronically) contracted muscle (we discuss lengthening the hamstring below, and provide a **Video 1** in the supplementary materials should the reader wish to have a first- or third-person experience of such a lesson). As above, the possibility of inhibiting a habitual movement may become easier as one attends to earlier phases of movement initiation. While performing a habit one whishes to reduce might seem at first paradoxical, it is in line with the above models of action goal selection in which inhibition and selection are flip sides of the same mechanism (Mostofsky and Simmonds, 2008; Cisek and Kalaska, 2010), and ATM suggests that the level of higher-level volitional control required to *inhibit* a habit may be acquired by first learning to volitionally *select* the habit.

Coordinating Physical Movement: Inhibiting Muscular Contraction

In this first of two example lessons for mindful movement, we focus on a narrow outcome—the neural control of the length of a muscle. This simple but important skill provides a foundation for considering how more complex or abstract skills might be practiced. Since muscular activity can only produce contraction, the neural mechanism for lengthening a muscle effectively comprises the *inhibition* of chronic or habitual signals that dysfunctionally contract the muscle while the opposing muscle contracts. Stephens et al. (2006) claim to provide the first demonstration of increasing the range of movement for lengthening a muscle (the hamstrings) *without* stretching or other forms of strenuous physical exertion but by providing sensorimotor *information* (i.e., experience) via mindful movement exploration. The development of such a skill may provide a foundation for other forms of behavioral inhibition, and may be an important component of training targeting ADHD impulsivity symptoms. In Stephens et al.'s study, participants showed increased knee extension measured in standardized conditions after engaging in ATM practice over the course of 3 weeks (as noted above, a recording of one such lesson is provided for demonstration in the **Supplementary Video 1**). Given the lack of stretching or exertion during the gentle movement of ATM practice it is unlikely that these increases in range of motion were the result of tissue strain and subsequent remodeling. Rather, they argue that the observed increases in knee extensions were the result of novel coordination patterns for the hamstring *and* related muscles. Consistent with our theoretical model of skilled control, this could be explained when mindful movement encourages the student to acquire (and actively select) more functional alternatives in a process of observing, and inhibiting movements and muscular effort that result from *habitual* selection of co-occurring motor commands that are not necessary or that even interfere with the execution of the movement goal (Stephens et al., 2006).

Importantly, however, research published prior to the Stephens et al. study failed to detect hamstring muscle lengthening in groups that practiced ATM in comparison to controls (James et al., 1998; Hopper et al., 1999). James et al. (1998) suggested that this lack of an observed effect may have been for a number of reasons. For example, there may have been a problem with the "dosage" of ATM lessons directed toward lengthening the hamstring muscles (e.g., duration of practice or number of lessons). Yet more relevant to our theoretical inquiry is the possibility that James et al.'s ATMs may not have provided sufficient opportunity to build stable associations and procedures. While ready transfer of abstract structures is observed between effectors (Keele et al., 1995; Braun et al., 2009), this has been (to our knowledge) uniformly observed in tasks where subjects *immediately know how to perform the initial task*. Skill learning is then observed via increases in accuracy, speed, or automaticity. James et al. may have been operating under the assumption that any ATM should yield abstract, transferrable skill to lengthen any of one's muscles—their intervention included 4 ATM lessons, but only 1 lesson was directed toward lengthening hamstring muscles. In the case of lengthening the hamstring, however, the student must gain a novel ability to inhibit a habitually contracted muscle. As such, a period of motor "concept formation" (perhaps more akin to motor "development" than "learning") may need to precede the "conceptual" level, in which the student focuses on specific sensorimotor details until coherent patterns are learned. Such constraints may apply to learning novel executive or attentional "concepts" (e.g., structural procedures) as well—sustained practice may likewise be required on a specific focus before abstract, transferrable attentional or executive skills are developed.

Certainly, we should exercise extreme caution in drawing theoretical conclusions from a handful of studies, but these findings provide examples of how we might rigorously evaluate the specificity of newly learned skills in the context of mindful movement training. By providing a set of lessons that explore, say, enhanced quality of movement *in general* vs. a targeted set of lessons with a precisely specified outcome (such as lengthening

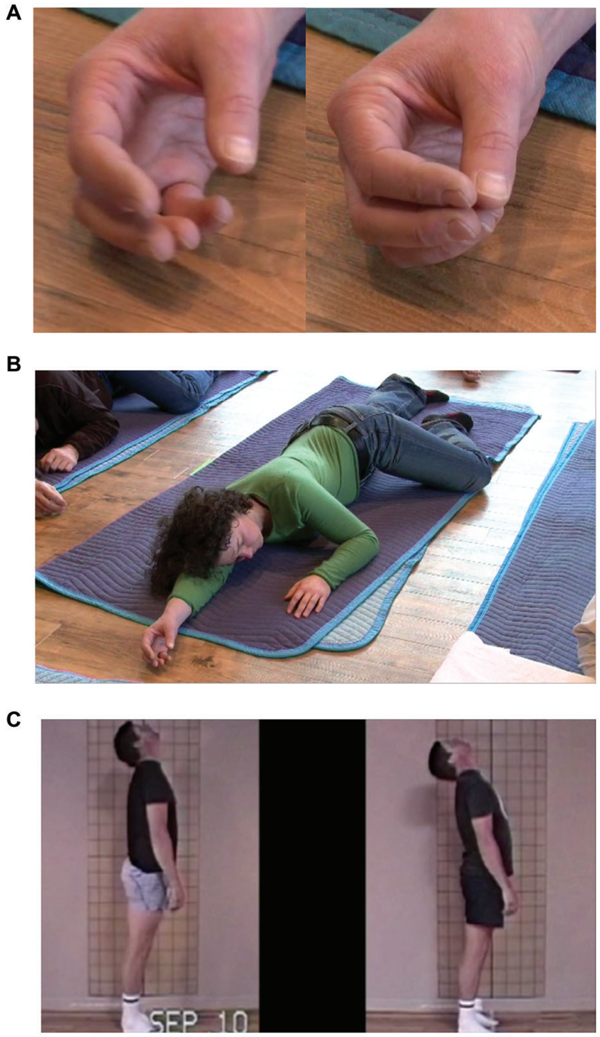

FIGURE 3 | (A) and **(B)** Frames from Awareness Through Movement (ATM) supplementary videos 2 and 3 demonstrating "motoric mind wandering." **(A)** *Introducing the dual task*. An excerpt from Haller (2014), vol. 2, disc 3. The student learns to perform a rhythmic movement of the hand while doing another movement (see **Supplementary Video 2**). **(B)** *Increased challenge*. The student struggles to remain engaged with the rhythmic movement of her hand while doing another challenging movement. The overall goal is to learn to coordinate control and attention to perform both movements simultaneously (see **Supplementary Video 3**). **(C)** Frame from supplementary video 4 demonstrating effects of ATM. A group of Seattle 18 fireman volunteers took part in a one week pilot program of Body Awareness Training based upon the teachings of Moshe Feldenkrais. Video data was collected before and after the training to establish quantitative measures of improvement. The man in the video was a supervisor and not as exposed to physical demands. But, changes are evident (see **Supplementary Video 4**). Provided with permission of Jeff Haller.

the hamstring), we may be able to demonstrate the focus necessary to *efficiently* and *reliably* learn the building blocks of novel skills. Having established specific skill gains, we might further explore if mindful practice yields the ability to transfer learned structures to novel movement contexts, or even to more abstract skills.

BOX 1 | Objective improvements.

Martial artists (including Feldenkrais) employ similar strategies, for example in "moving while sensing tanden," in which participants are instructed attend to their lower abdomen—the tanden—while performing various movements. The movements are distracting; the whole lesson is about learning to regain attention of the tanden. An even more universal instruction is to maintain focus on the breath (notably including FA meditation). In tai chi, there are universally applied principles like groundedness and stepping with an empty leg (Wayne and Kaptchuk, 2008a; Wayne, 2013). In Yoga, there are aspects of the breath that are monitored and controlled (Gard et al., 2014a). In ATM, there are likewise general concepts such as reversibility of movement, connectedness to the support surface, sensitivity to habitual motor impulses, reduction of unnecessary muscular effort that are intended to be a part of every movement performed (Feldenkrais, 1972). The advantage of an overt hand movement (as in the "motoric mind wandering" example) is that outside observers can also (categorically) detect when the student "wanders" (readers may verify this for themselves with the videos in the supplementary material). Novel movement instructions, particularly those that provide attentional challenges may additionally yield an initial feeling of awkwardness when doing a "lesson", which may gradually reduce as the student improves. Feldenkrais speaks of ultimately becoming "elegant" in one's movements, which may provide additional externally observable criteria for indexing gradual improvements during learning.

Coordinating Attention: Motoric Mind Wandering as a Context for Practice

Above we also discussed a more high-level form of sensation and information—the detection of mind wandering—as the first step of FA meditation practice. While a common practice of FA meditation is the more "cognitive" maintenance of single-pointed attention, in a second example lesson we illustrate higher-order goal-maintenance as an aspect of movement practices. A motoric analog of FA is for example provided in the "flex hand to stand" ATM (recordings are provided in the **Figures 3A,B** and the **Supplementary Video 2** and **Supplementary Video 3**). This lesson aims to provide a motoric context for detecting failures of task-relevant goal maintenance. The student is instructed to rhythmically perform precise configural movements with the fingers of one hand (a motor paradigm that is known to strongly engage dorsal premotor cortex; Verstynen et al., 2005) and in addition perform a second motor task—rolling with the torso to one side. The overarching goal is for the student to perform both tasks simultaneously. However, when attention becomes too absorbed in the details of rolling, the movement of the hand stops (or becomes tense or stiff), in essence creating an observable moment of "motoric mind wandering" (including changes in overall movement quality or motor tonus). The student thus finds himself in a whole body sensorimotor situation designed for the practice of goal-maintenance in a context of overtly observable mind wandering (or "motor-wandering").

While the above ATM lesson may provide a particularly clear analog for the "cognitive" practice of FA meditation, the general strategy of embedding continuous monitoring and maintenance of global aspects within a set of local movements is shared with other practices like tai chi and yoga (see **Box 1**). Continuous monitoring and maintenance of higher-level qualities of movement may provide an embodied and engaging context to practice cognitive skills, and we propose that this is likely central to potential cognitive improvements observed from such practices. As with the lesson above on "lengthening the hamstring, it may be that sustained practice on a well-defined "mind wandering" challenge may be more effective than highly varied practice. In tai chi, for example, one could imagine providing beginning students with a consistent attentional focus for the first few weeks of practice, only switching after students were able to create the building blocks of a novel attentional skill.

Conclusion

We have evaluated the potential of mindful movement practices to improve the control of attention, both in typical and in pathological cases. Cognitive, neural, and developmental perspectives point to a shared capacity for inhibition and selection that spans basic motor processes and higher-order cognitive control. At the neural level, we have highlighted the role of frontal regions that are arranged in a hierarchy from primary motor, to premotor, on to prefrontal cortices in supporting the formation, selection and execution of procedures that coordinate action over time and space, in concert with parietal and subcortical regions (Fuster, 2001). Given a reciprocal contribution of motor processes to executive control and of executive control to (higher-level) motor processes, a practice based on movement may provide an integrated opportunity to improve the control of attention—in movement and otherwise.

Based on evidence for a functional contribution of the (higher-level) motor system to executive processes of attention and cognitive control across pathological and typical populations, we suggest modeling the deployment of attention as a motor skill process. Our model of *skillful attention* hypothesizes a possible mechanism for attentional and executive control in procedural skills that organize reciprocal inhibition and selection of candidate goals and actions within shared executive processes between movement, attention and cognition. As with other skills, our model predicts that executive control of attention can be improved by obtaining a robust coordination of goals, attention, and action. In classical skill learning, the accumulation of a conceptual or "declarative" knowledge base is critical to this process, though we suggest that the accumulation of *novel functional procedures* will ultimately dominate fluent performance in later stages of skill learning. Neural changes would likely include initial enhancement of prefrontal activity that decreases as procedures become established as *sensorimotor* procedures via a process for instance of hebbian or reinforcement learning. Following the skill literature, robust goal-directed action is obtained when the continued practice of initial "cognitive" strategies builds up a repertoire of procedural associations between attended sensations, goals, and actions. We highlight a *mindful* mode of learning skills (Salomon and Globerson, 1987; Langer, 2000) via movement (Feldenkrais, 1981) based less on effort but more on fostering sensitivity to variation and active exploration. In contrast to effortful repetition to strengthen a single given way of acting, mindful learning enhances the repertoire of alternative procedures available to achieve a given goal. We propose that a more effortless mindful mode of learning may yield a more abstract structure of the procedures that are learned. As stated above, how one learns is as important as what one learns. Further, if the practice is interesting and engaging, even initial practice may be driven more by interest in mastery of the practice than by endogenous effort towards a goal (Leonard, 1992; Langer, 2000). Thus, notwithstanding improvements of cognitive control via effortful focusing of attention, we suggest investigating an alternative approach in which robust structural procedures for guiding attention are acquired via mindful practice of an engaging movement-oriented skill.

A movement practice moreover provides the opportunity to train procedures for inhibition and selection in the context of the natural sensorimotor loop, in which physical actions *generate* concretely observable sensory consequences. In particular, while it is difficult to sense the status of goals, intentions, or thoughts, movement provides concrete, readily observable phenomena that will proceed from an enacted motor plan. Mindful comparison between expected and observed outcomes may provide clear signals for error-driven learning processes (as supported by predictive processes of movement control in prefrontal cortex and the cerebellum). We suggest this entrainment of the sensorimotor loop is a strong argument to examine the domain of motor practice: the practitioner has the scaffold of a physical, sensory context as they grapple with attentional control, and likewise, as researchers, the results of successfully selected (or unsuccessfully inhibited) movements result in readily measurable outcomes (i.e., overt movements, EMG). The motor system additionally provides an opportunity to probe for cortical inhibition via TMS SICI (discussed in the section A Motor Perspective on Attention and Self-Regulation), and may provide a further opportunity for distinguishing between the effects of motorically grounded practice and more "cognitive" practices. The variety of potential movement trainings may also provide for specificity with improved behavioral inhibition resulting from a practice of inhibiting habitual muscular efforts, and attentiveness being improved via lessons that challenge the coordination of attention (as in the motoric mind wandering lesson above).

Challenges to a Motor Skill Theory of Attention

While we claim that our expansion of motor skills to include cognitive control has already been productive, it is by no means definitive. We note that skill is not a monolithic concept, and we might be accused of mapping one complex system onto another arbitrary complex system. To guard against this, it is necessary to clearly specify a computational model for a given set of tasks, along with expected biologic correlates. The challenge remains to find an appropriate balance between a holistic account on one hand, and a sufficiently specific and falsifiable account on the other. In particular, we have argued that "structural" (i.e., abstract, transferrable) procedures are critical to our proposed mechanism for cognitive and attentional effects of mindful movement training. While the nature of transferrable motor procedures dates back to the early days of skill research (i.e., Fitts and Posner, 1967; MacKay, 1982; Bernstein, 1996), it remains an open and novel research question to develop clear computational and neural models of abstract *procedures of attention*. In particular, a plausible alternative to our procedure account is a capacity account, in which prefrontal and premotor networks implicated in motor and attentional control are generically "strengthened" with practice. Without clear specification and approaches to measuring abstract attentional procedures, it is difficult to distinguish a capacity from a skill (or procedural) account. This highlights the central role of improving our characterization of attentional and other abstract cognitive procedures in order to progress with our theory. Fortunately, experimental cognitive science has already provided a number of paradigms for assessing attentional and cognitive control, and performance on these paradigms is not perfectly correlated (cf. Kipp, 2005), and thus may already provide a way to index different abstract procedures.

Our skill framework may also not apply to all approaches to mindfulness. For example, FA may rely less on a skill base of procedures, and more on a conceptual or "declarative" knowledge base. Elsewhere in this issue, Russell and Arcuri (2015) argue for the centrality of mindfulness that is closer to FA meditation than our conception of mindful learning for effective clinical movement training (they term their approach "contemplative movement" in contrast with "mindful movement" like tai chi, yoga, or Feldenkrais). While enhanced control of *somatosensory* attention *is* seen in "standard" meditation approaches (Kerr et al., 2013), this may reflect a focus on bodily sensation during meditation training that is not shared among all traditions. As opposed to a focus on sensation processes, some teachers of insight approaches may suggest distancing one's self from discomfort while sitting still, and other paths may direct students to abstract affective foci such as "loving kindness" or compassion. These profound differences in the deployment of attention between forms of mindfulness training likely do different things, and have different neural bases. To understand them, we must differentiate their mechanisms—or within our framework, identify foundational procedures and knowledge. Both traditional and contemporary mindful movement practices are complex multi-component interventions in comparison to laboratory paradigms (Wayne and Kaptchuk, 2008a). In particular, we have only mentioned the possible role of reward and motivation for skill learning, even though motivation is highlighted by Feldenkrais (1981) and Langer (2000), and has also been a recent focus of interest in formal models of skill learning (e.g., Oudeyer et al., 2007; Metzen and Kirchner, 2013; Santucci et al., 2013), reward-based neuronal decision making (e.g., Gottfried et al., 2003; Daw et al., 2006; Pessiglione et al., 2006), and—particularly relevant for our approach—in relation to effort (Kurniawan et al., 2010) vs. novelty (Wittmann et al., 2007).

Crucially, we also have not attempted to provide a complete overview of the Feldenkrais method—let alone the full breadth of mindful movement practices—and these other aspects may be critical to gain the full value of the practice. For instance, we have only hinted at the detailed exploration of biomechanical configurations offered in ATM. Likewise, we have only started to delve into Feldenkrais' deep philosophical commitment to a movement basis for the development of our minds, which beyond shared resources of movement, sensation and cognition also includes emotions (Feldenkrais, 1972, 32). More critically, we have not described Feldenkrais' assumed model of optimal organization, including the use of skeletal as opposed to muscular support in gravity, or structuring the movement system so it allows immediate initiation of a novel movement plan with minimal hesitation and preparation. For an accessible, practical introduction, see Feldenkrais (1972), or for a more theoretical treatment, see Feldenkrais (1981). For a more complete overview of yoga, see Gard et al. (2014a) and for tai chi, Wayne and Kaptchuk (2008a,b). Perhaps most critically, much work remains to establish whether mindful movement approaches are reliable and efficacious (though we have mentioned similar concerns regarding standard treatments for ADHD in section A Motor Perspective on Attention and Self-Regulation). While we have provided multiple lines of evidence for our selected aspect of improving cognitive control and attention via mindful movement, we can only definitively claim that we have identified promising opportunities for investigation.

A Motor Skill Orientation to Training Attention

Strong support for our motor skill framework comes from the co-occurrence (and correlation) of motor and cognitive difficulties in abnormal development (Diamond, 2000), and in particular in the case of ADHD (Mostofsky and Simmonds, 2008). We provide an explanatory scheme that foundationally incorporates the co-occurring motor/cognitive disorder. Our model of skilled attention is based in a well-understood link between motor system and cognition via shared processes of inhibition/selection that are supported by a hierarchy of frontal regions (embedded within a larger network). This link provides behavioral and neural motor measures that complement measures such as go/no-go and stop signal tasks, and are particularly relevant for relating sensorimotor improvements to more cognitive improvements in a movement practice. Given the lack of long-lasting interventions for ADHD (and other disorders), and the theoretical basis we have presented, there is the potential that our proposal may isolate core features of developmental challenges (rather than symptoms), which may have tremendous benefit. In particular, two of the authors are currently exploring the impact of a mindful movement training on TMS SICI in ADHD. This approach provides the rare ability to assess changes in causal neural mechanisms of low-level motor inhibition.

A large body of research demonstrates that a putative basis of improved mental abilities, neural plasticity, is driven by activity dependent learning mechanisms. Their main characteristic is that the neuronal hardware adapts in functionally specific ways to the particular experience of the organism (for reviews of a broad range of neuronal plasticity results, see e.g., Kaas, 1991; Buonomano and Merzenich, 1998; Simoncelli and Olshausen, 2001; Sur and Leamey, 2001; Pascual-Leone et al., 2005). As a computational consequence, a central question for training-based improvements of neuronal functioning is the ability to drive the desired neural activity, and hence, plasticity. If, as we suggest, movement and cognitive control consist of procedures for selection and inhibition across sensorimotor and goal representations, mindful *movement* training demonstrates a profound potential to improve cognitive function and attention in ADHD and the general population. Experimentally, we would expect the *content* of the skill (e.g., improvements in trained movements) to increase alongside changes in motor system measures such as mirror overflow or TMS SICI as well as measures of attention and executive control. Our first feasibility trial is currently underway to determine whether we can detect clear relationships between "cognitive" clinical improvements and measures of motoric function in the administration of mindful movement to adolescents with ADHD. Experimenters and clinicians can test our theory by measuring (and reporting!) improvements in movement skill (e.g., in addition to clinical targets) as we seek to understand the basis for improved attentional and cognitive control from mindful movement interventions.

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Supplementary Materials

The Supplementary Material for this article can be found on figshare. Links are provided below:

Supplementary Video 1 | Lengthening the Hamstrings Awareness Through Movement (ATM) Lesson. An excerpt from chapter 2 of Haller (2014), vol. 9, disc 1. The full movement lesson is included, followed by the initial class discussion. The lesson may be used to provide a first-person experience, or for third-person observation of students doing the lesson. Provided with permission by Jeff Haller. **Supplementary Video 1** is available at: http://dx.doi.org/10.6084/m9.figshare.1448106

Supplementary Video 2 and 3 | Awareness Through Movement (ATM) demonstrating "motoric mind wandering". An excerpt from Haller (2014), vol. 2, disc 3.

Supplementary Video 2 | Introducing the dual task. The student learns to perform a rhythmic movement of the hand while doing another movement. **Supplementary Video 2** is available at: http://dx.doi.org/10.6084/m9.figshare.1447886

Supplementary Video 3 | Increased challenge. The student struggles to remain engaged with the rhythmic movement of her hand while doing another challenging movement. The overall goal is to learn to coordinate control and attention to perform both movements simultaneously. Provided with permission by Jeff Haller. **Supplementary Video 3** is available at: http://dx.doi.org/10.6084/m9.figshare.1447842

Supplementary Video 4 | Effects of ATM. A group of Seattle 18 fireman volunteers took part in a one week pilot program of Body Awareness Training based upon the teachings of Moshe Feldenkrais. Video data was collected before and after the training to establish quantitative measures of improvement. The man in the video was a supervisor and not as exposed to physical demands. But, changes are evident. Provided with permission by Jeff Haller. **Supplementary Video 4** is available at: http://dx.doi.org/10.6084/m9.figshare.1453157

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Conflict of Interest Statement: One of the authors (Dav Clark) has completed a Feldenkrais teacher training. Since we do not contribute to the literature on the clinical efficiency of mindful movement training but rather present a novel theoretical concept that may help to explain and operationalize the effects of a broad range of mindful movement practices as trainings of cognitive control, we do not see a conflict of interest. The other authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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The preparatory set: a novel approach to understanding stress, trauma, and the bodymind therapies

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Basic to all motile life is a differential approach/avoid response to perceived features of environment. The stages of response are initial reflexive noticing and orienting to the stimulus, preparation, and execution of response. Preparation involves a coordination of many aspects of the organism: muscle tone, posture, breathing, autonomic functions, motivational/emotional state, attentional orientation, and expectations. The organism organizes itself in relation to the challenge. We propose to call this the "preparatory set" (PS). We suggest that the concept of the PS can offer a more nuanced and flexible perspective on the stress response than do current theories. We also hypothesize that the mechanisms of body-mind therapeutic and educational systems (BTES) can be understood through the PS framework. We suggest that the BTES, including meditative movement, meditation, somatic education, and the body-oriented psychotherapies, are approaches that use interventions on the PS to remedy stress and trauma. We discuss how the PS can be adaptive or maladaptive, how BTES interventions may restore adaptive PS, and how these concepts offer a broader and more flexible view of the phenomena of stress and trauma. We offer supportive evidence for our hypotheses, and suggest directions for future research. We believe that the PS framework will point to ways of improving the management of stress and trauma, and that it will suggest directions of research into the mechanisms of action of BTES.

Keywords: somatic experiencing, preparatory set, body-oriented psychotherapy, stress, mind-body, trauma, post-traumatic stress disorder, meditative movement

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Introduction

This paper is in response to two challenges: first, we offer an alternative perspective on the concept of stress, and second, we provide a clearer understanding of the mechanisms of action of body-mind therapeutic and educational systems (BTES). We propose the concept of the Preparatory Set (PS), defined as the unitary, largely subcortical, organization of the organism in preparation for response to environmental conditions. We address stress and BTES in the same discussion because we hypothesize that the maladaptive PS is the cause of stress, and that the effectiveness of BTES largely depends on addressing maladaptive PS. We suggest that these concepts offer a way of understanding the BTES, as well as a broader and more flexible way of understanding the phenomena referred to as "stress."

Stress

The term "stress" is widely used, and its significant contribution to human disease and suffering is well recognized (Kemeny and Schedlowski, 2007; Chida et al., 2008; McEwen, 2008; Fagundes et al., 2012; Van der Kolk et al., 2012; Everly and Lating, 2013). However, the term is often poorly defined. It has been used to refer to a subjective state, a physiological reaction, a neurochemical response, or the presence of a certain kind of external situation. For a review, see (Everly and Lating, 2013). Over 50 years after the first use of the term, there are enough questions left unresolved that we suggest that a different way of looking at these phenomena is needed. Below we list these key questions:

- What is the difference between "good" stress and "bad" stress?
- What distinguishes acute, chronic and traumatic stress, apart from the differing physiological responses?
- What is resilience to stress?
- What is appraisal, and how does it influence the stress response?
- What is the actual nature of stress, apart from its neurological and neurochemical correlates?

Simple physiological definitions of stress in terms of prolonged sympathetic arousal do not appear to answer these questions. We propose that the concept of the PS can clarify these issues.

BTES

BTES, including meditation, meditative movement, Somatic education and body-oriented psychotherapies, offer approaches to alleviating human suffering that differ substantially from mainstream pharmacological, cognitive, exposure and exercise interventions (Everly and Lating, 2013). BTES address the person as an integrated whole, an approach quite different from the bio-medical approach of isolating, analyzing and treating the functioning of separate systems. BTES use movement, proprioception, interoception, posture, and various ways of attending to the body and bodily experience, rather than cognitive methods or conventional exercise approaches (Wright, 2000; Stuart, 2013; Kimmel et al., 2015). These factors have made it difficult for researchers to find appropriate conceptual frameworks for studying BTES (Kerr, 2002). As a result, despite substantial clinical and anecdotal evidence for efficacy, most BTES have not been well researched (with the exceptions of mindfulness meditation (Holzel et al., 2011a; Vago and Silbersweig, 2012; Tang and Posner, 2013) and Yoga (Roberts, 2013; Gard et al., 2014; Riley and Park, 2014).

The Preparatory Set

History

The term "preparatory set" has been in use in the scientific literature at least since 1918, in the context of studies of reaction time (Henmon, 1918). In subsequent decades the term was used in a number of contexts, and alternate names were used such as "organic set" (Young, 1925) and "quantitative set" (Bills and Brown, 1929). In 1941 Gibson critiqued the excessively broad use of the term (Gibson, 1941), and subsequent to that the term came to be used mainly in the context of the influence of cognitive expectation on perceptual and motor reaction time (Ruge et al., 2013).

Here we use the term to refer to the rapid, largely sub-cortical, preparation of the organism for response to the environment. We suggest that this preparation involves an organization of core features of the organism in readiness: physical posture and muscle tone, visceral state, affective or motivational state, arousal and orientation of attention, and (subcortical) cognitive expectations. This PS precedes, and influences, the complex human cortical responses of conscious appraisal and voluntary planning.

Preparation and Response

We suggest that an organism's response to the environment can be seen as having 3 phases:

- initial noticing and orienting to of the situation;
- preparation of response;
- execution of response (e.g., run away, run toward).

These phases do not necessarily follow a linear course; for instance, the execution of a response may be interrupted by a re-evaluation and preparation for an alternate response (Resulaj et al., 2009).

The initial orienting phase is unconscious, automatic and controlled by the brain stem reticular formation, especially the caudal areas which mediate generalized cortical and somatic arousal (Sokolov, 1963; Sarter et al., 2003). These rapid and automatic processes are not included in the preparatory response. Bull, in her attitude theory of emotion, also distinguishes between the preparatory response itself and the initial unconscious automatic reflex response (Bull, 1951).

Following this is the *preparation* for response. We suggest that this is a rapid, largely subcortical response; although it is not fully unconscious it is distinct from the conscious rational appraisal and voluntary decision-making process mediated by the cortical executive networks. It is an integrated readying of the whole organism to take action, and involves simultaneously posture, autonomic activity, affect, attention, and expectation. This phase is our principal focus.

The action phase, which follows, is the performance of the prepared response. It may happen almost immediately, after a delay, or not at all. Proprioceptive and exteroceptive feedback will inform the organism about the successful completion of the action (Gellhorn and Hyde, 1953; Suetterlin and Sayer, 2013), following which a new PS may form (See **Figure 2**).

The Five Elements of the PS

The PS involves integrated action of the subcortical systems controlling muscle tone and posture, autonomic/visceral state, affect, attentional arousal, and expectation. It is a key point in our hypothesis that these all tend to respond together, as different facets of a single process. We hypothesize therefore that intervention in any one of these five aspects will tend to influence the others; for example, that changing posture may alter affective state, or changing the direction of attention may alter the autonomic state. We suggest that this hypothesis can explain the effects of the BTES, which use exactly these types of interventions. There is already significant evidence for strong mutual influence of many of these. Below we discuss each in turn, describing its function briefly and presenting evidence for its influence on other aspects of the PS (See **Figure 1**).

Posture, Muscle Tone, and Breathing

Posture, muscle tone and breathing are closely interrelated. We choose here to discuss them together; to discuss them separately would add complexity to an already complex subject. The words "posture," "attitude," and "stance" can be used in multiple ways, as in: physical stance, emotional stance, cognitive stance. We believe this apparently metaphorical similarity points to the underlying reality of the intrinsic connection between posture, emotional attitude and cognitive attitude as hypothesized in the concept of PS.

Movement and posture

Preparation for movement involves the adoption of a posture. "Posture" here does not mean a completely static position, but a dynamic preparatory state involving small motions and changes in muscle tone. It may be distinguished from overt consummatory movements (such as running, reaching or eating). All behavior involves a continual shifting between preparatory and action phases.

Postural preparation underlies movement; and movement underlies life. Sperry has referred to the brain as a "motor brain" (Sperry, 1961). However the relation of motor function to affect and cognition remained relatively unexplored until the past decade (Downing, 2000). Proprioception refers to information coming to the brain about the position and movement of the body and is essential for coordinated movement (Sainburg et al., 1995; Riemann and Lephart, 2002). It comes principally from the muscle spindles and joint receptors, Pacinian corpuscles and free nerve endings in the connective tissue (Riemann and Lephart, 2002; van der Wal, 2009), and the vestibular apparatus. This information may be conscious or unconscious, and training can increase awareness of it (Hewett et al., 2002; Tsang and Hui-Chan, 2003). It has not received as much attention as interoception, but we suggest that it has an importance far beyond the mechanical coordination of the body.

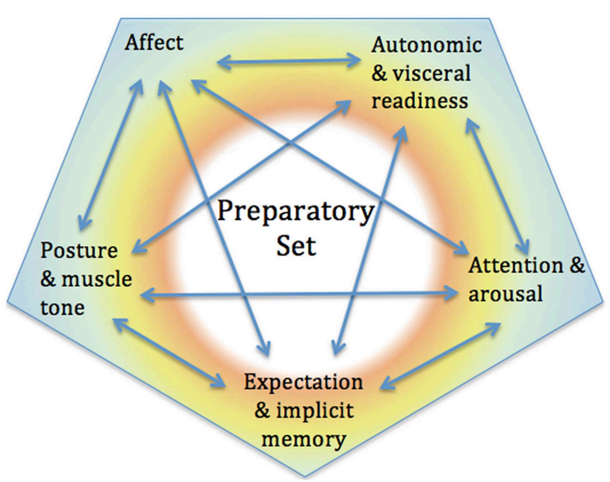

FIGURE 1 | The preparatory set and its five elements: affect, posture, and muscle tone, autonomic state, attention, and expectation all influence each other, forming a unitary response.

Developmental aspects of posture

Posture and movement have been shown to be crucial for the early development of personality. Movement and the sense of movement are among the first abilities to develop in the infant (Thelen, 1995). Disturbances at this phase of development may profoundly damage later affective and cognitive development (Thelen, 1995). An infant's first communication is gestural/postural animation. This forms the basis for the later acquisition of language (Sheets-Johnstone, 2011; Esteve-Gibert and Prieto, 2014). Newborn infants imitate the bodily movements of adults (Meltzoff and Moore, 1983); infant development comes about largely through physical engagement of movement in relation to caregivers (Smith and Gasser, 2005). This suggests a central role for movement and movement preparation. Haselager (Haselager et al., 2011) conjectures that awareness of movement forms the basis for the development of the sense of self. The simulation of bodily experienced states and actions are significantly involved in memory (Ross et al., 2007), understanding (Barsalou et al., 2003; Pulvermüller, 2005), interpersonal communication (Hostetter and Alibali, 2004), social interaction (Sebanz et al., 2006), and spatial perception (Tversky, 2003). This supports the idea that postural and bodily aspects of the PS are intrinsically linked other aspects such as expectation, affect, and awareness.

Mechanical aspects of posture

Prior to an action "anticipatory postural adjustments" are made, anticipating the displacement of the body or body parts along a pathway toward a goal (Massion, 1992) and maintaining direction of attention and support of the center of gravity by the ground (Jung, 1981). Direction of attention and stable support are necessary for accurate organization of postural adjustments and controlled movement (Massion, 1994). These "reference cues" (Gurfinkel et al., 1981) integrate with internal representations of posture, especially the longitudinal axis of the body and its relation to gravity and support feedback (Macpherson et al., 1989; Mitteltaedt, 1989). We believe that emotional posture is closely linked to these mechanical aspects of posture (Weisfeld and Beresford, 1982; Bianchi-Berthouze et al., 2006). Postural preparation is functional, in that a certain goal is being prepared for (e.g., to attack or to run away). Some BTES work extensively with this aspect of posture. We suggest that conscious proprioceptive awareness of reflex postural preparedness may give rise to pleasant experiences of stability, readiness, and self-efficacy, or unpleasant feelings of lack of confidence and anxiety. See below for ways of testing this hypothesis.

Breathing likewise has a mechanical aspect, closely linked to posture in that efficient breathing and efficient posture support each other. It also has an autonomic and affective aspect. Voluntary control of breathing has been demonstrated to alter autonomic and affective state (Brown and Gerbarg, 2005a; Chan et al., 2010; Busch et al., 2012; Sano et al., 2015). Breath control is a key intervention in most BTES.

Emotional aspects of posture

Facial expression has long been recognized as an inherent aspect of emotion (Ekman et al., 1983; Levenson et al., 1990); engaging the smiling musculature produces positive affect (Strack et al., 1988). However the role of bodily postural expression has been less investigated. De Gelder (2006) proposes the term "emotional body language" (EBL) to refer to the characteristic postures and subtle movements of the body that express and communicate emotion. She suggests facial expression and bodily posture are two facets of a single process. Like facial expression, EBL is largely automatic rather than voluntary, and is controlled by a subcortical network involving the amygdala, pulvinar, striatum and superior colliculus; fully conscious experience of EBL is mediated by insula, somatosensory cortex, anterior cingulate and ventromedial prefrontal cortex, and the perception of EBL in others by yet another network. In experiments involving the identification of emotion from photos, EBL was shown to be less ambiguous than facial expression, possibly because it shows the intended action more clearly (de Gelder and Hortensius, 2014). This supports our suggestion that intended action is a key aspect of affect as well as affective posture.

There is significant evidence for the connection between posture and emotional and cognitive states. The recently developed fields of embodied cognition (Varela et al., 1991; Wilson, 2002) and grounded cognition (Barsalou, 2008) offer many examples. Voluntary alteration of posture has been shown to influence risk behavior (Carney et al., 2010). An expansive posture induced a rise in testosterone, and a contracted posture induced a rise in cortisol (Carney et al., 2010). Smiling (a "posture" of the face) induced positive feelings and a slumped posture produced negative affect (Strack et al., 1988; Stepper and Strack, 1993). Thinking words related to pride alters posture (Oosterwijk et al., 2009); and a collapsed posture increases depressive thought (Weisfeld and Beresford, 1982).

Holstege's concept of the "emotional motor system" (EMS) (Holstege et al., 1996), supports these ideas. The EMS operates independently of the voluntary cortical control of movement, and is responsible for muscle tone and core body posture as well as expressive gesture. Holstege mentions that patients with pyramidal tract injury paralyzing the facial muscles can still smile in response to an emotional feeling (Holstege et al., 1996). Yawning, stretching and other reflexive function can occur even in the presence of extensive pyramidal lesions (Töpper et al., 2003). These findings support the existence of a subcortical connection between affective state and facial and bodily expression.

Panksepp, in considering the brain structures supportive of the core sense of self, regarded motor function as essential and definitional; he points to the periaqueductal gray (PAG) and surrounding midbrain regions as a prime candidate (Panksepp, 1998). The PAG also plays a central role in the EMS as hypothesized by Holstege (2013), and is centrally involved in the organization of integrated defensive and appetitive responses (Bandler et al., 1991). Panksepp suggests that at this basic level movement is inseparable from affect (Panksepp, 1998); we hypothesize these structures (PAG and adjacent midbrain nuclei, limbic region, and basal ganglia) form the principle neural substrate for the PS.

Autonomic Response

The autonomic nervous system (ANS) readies the body for appropriate response to environmental challenge. It controls the activation of the cardio-respiratory system, the gastro-intestinal tract, sweat glands, hair follicles, and pupillary dilation via the sympathetic and parasympathetic nerves, as well as controlling aspects of the endocrine system by way of the pituitary. The ANS also strongly influences the motor system, controlling muscle tone via activation of the gamma efferent neurons, which influence the responsiveness of the muscles in preparation for complex defensive or appetitive movements (Kennard, 1947; Gellhorn, 1953, 1967a; Hamm et al., 2003). Electrical stimulation of the hypothalamus (the principal controller of the ANS) is known to produce coordinated defensive or appetitive responses accompanied by signs of emotional arousal (Hess, 1925; Gellhorn, 1970) via projections to midbrain nuclei (PAG, locus coeruleus) and the pontine and medullary reticulum (Gellhorn, 1967a). Any activation of the muscular system also involves circulatory and cardio-respiratory adjustments mediated by the ANS; significantly for the PS concept, even imagined movement activates an autonomic response appropriate to the anticipated exertion (Collet and Guillot, 2010). The ANS is strongly linked to the subcortical affective centers, and there is evidence that each emotion has a specific autonomic signature (Ekman et al., 1983; Levenson, 1992; Hamm et al., 2003).

Early concepts of the ANS regarded it as a simple reciprocal bivalent system composed of a sympathetic and a parasympathetic division, which stimulated or calmed visceral functioning (Hess, 1925). Hess (1925), an early researcher into the functioning of the hypothalamus, recognized that the ANS did not function in isolation but was part of an integrated response including the motor system, the arousal/attentional system, and neuro-humoral response. He used the terms ergotropic (energy-seeking) and trophotropic (nourishment-seeking) to refer to the integrated functioning associated with the sympathetic and parasympathetic systems respectively. These terms have fallen into relative disuse, but they facilitate description of our concept of unitary subcortical action, and we will use these terms in this paper.

The bivalent view of the ANS has been replaced by a view of the ANS as being capable of complex and nuanced responses to varied circumstances (Saper, 2002). Gellhorn (1970), Levine (1977), and Berntson (Berntson et al., 1994) demonstrated that sympathetic and parasympathetic branches were not limited to reciprocal action; the could vary independently, or co-vary in the same direction. Saper has shown that the hypothalamus is capable of orchestrating complex autonomic responses to varying physiological demands such as thermoregulation, hunger and thirst, and a range of emotional states (Saper, 2002).

Porges (2007) has suggested a three-fold division of the ANS: (a) the evolutionarily primitive, dorsal vagal system that promotes immobility and shut-down, (b) the sympathetic system that mobilizes the fight-or-flight response, and (c) the ventral vagal system that facilitates social engagement. On this basis

Porges identifies five global states, involving varying combinations of these: relaxed social engagement, vigorous social play, aggressive/defensive mobilization, relaxed resting immobility, and fear-based freeze or collapse (Porges, 2001). Each of these can be seen as a form of PS, involving coordinated autonomic, motor, affective, and cognitive states.

Interoception is the name given to the perception of information coming to the brain from the viscera (Vaitl, 1996); this also includes afferents from skin (Björnsdotter et al., 2010) and fascia (Schleip, 2012). Craig and Critchley have delineated the pathways whereby some of this information can reach consciousness and bring information about affective and autonomic state (Craig, 2002; Critchley et al., 2004) Damasio (Damasio et al., 1996) suggests that interoception may carry important information about the environment. It has been shown that even unconscious visceral afferents can strongly influence affective experience and behavior (Ádám, 1998). Training can enhance conscious awareness of interoception (Holzel et al., 2011b; Farb et al., 2013) and thereby increase emotional self-regulation (Vago and Silbersweig, 2012).

Emotional/Motivational Response

A widely held view is that emotion is strongly related to a disposition toward action (for instance (Bull, 1945, 1951; Lang et al., 1990, 1993; Frijda, 2004) Bull's attitude theory of emotion states that emotional affect emerges out of the preparation for action rather than the action itself (Bull, 1951, 1955). Her investigation of hypnotically induced emotion demonstrates that the preparatory movement responses to emotion constitute an integral aspect of the experience of emotion. If a certain preparatory movement state was (hypnotically) suggested to the subject (for instance, leaning back in the chair), they were unable to experience a (hypnotically suggested) emotion that contradicted this (for instance, anger) (Bull and Gidro-Frank, 1950). De Rivera (1977) extended Bull's work, offering a conceptual schema using five dimensions of movement to characterize a broader range of human emotional experience. His schema has not been investigated, beyond one study of consistency and reliability, but his ideas suggest the possibility of more detailed correlations between emotion and movement preparation. One possible line of investigation would be to produce abstract animations embodying the dynamics suggested by De Rivera ("move myself away from the other person," "move the other person away from me," etc.) and discover whether subjects attribute emotional motivation to the images.

Panksepp identifies seven core emotional systems (Panksepp, 2005), each associated with specific subcortical nuclei and neurotransmitter profile. He regards the motoric and affective aspects of these as equally important Each emotional system involves motivational feeling as well as characteristic movement and movement preparation patterns, supporting our hypotheses. He argues for these systems as the source of both human and animal basic emotions; his arguments are as follows.

- Direct brain stimulation in animals and humans produces strong unconditioned emotional reactions, whereas cortical stimulation has much less effect.
- The locations which produce such emotional responses are in homologous areas in all animals tested.
- All primary emotional responses remain intact after radical de-cortication early in life.
- In humans, severe damage to the insula, the visceral/affective cortex, does not eliminate emotional experience
- One can demonstrate that animals like or dislike stimulation of these areas, which can be used as reward and punishment
- When homologous brain regions are stimulated in humans, subjective experiences are reported which correspond with the animal behavioral responses.

For a detailed exposition see (Panksepp, 1998, 2005, 2011).

Attentional Response (Awareness)

Attending is an act as well as a receptive experience; and there is a spectrum from purely reflexive to fully volitional attending. Fan (Fan and Posner, 2004) proposes a distinction between alerting, orienting, and executive direction of attention. The initial alerting reflex is automatic and unconscious. It involves hippocampus, superior and inferior colliculus and the locus coeruleus, PAG, ventromedial medullary reticular formation, and medullary nuclei controlling head movement (Radulovački and Adey, 1965; Öhman et al., 2000). At this level a rapid automatic evaluation is already being made (Porges, 2004) and we suggest that the PS begins to be organized. Next a more complex and nuanced orientation process begins, directing the appropriate senses in the appropriate directions, orienting to available resources, and completing the PS process. More rostral areas become involved later: the parietal lobe and the frontal eye fields (for visual stimuli), and finally, with volitional direction of attention, anterior cingulate and prefrontal cortex (Fan and Posner, 2004). The exact point at which this process becomes conscious is not clear. We suggest a continuum of awareness from completely unconscious and automatic to fully conscious and voluntary, and that the training of voluntary attention may lower the threshold so that previously automatic responses may come under voluntary influence. Such alterations have been demonstrated, see for instance (Brown et al., 1984).

Affect influences attention at a fundamental level: for instance, negative emotions narrow and focus the field of attention in specific ways, whereas positive emotions open the attentional field beyond that of neutral attention (Fredrickson and Branigan, 2005). We hypothesize that this influence goes in both directions: voluntarily broadening the field of attention may induce a more positive affective state. BTES make such claims, which could be tested as described below.

The PS has been explored extensively in the context of simple perceptual attentional tasks, involving the study of anticipatory saccadic eye movements (Ruge et al., 2013). These studies are of limited relevance here as they deal with very short time frames and affectively neutral situations. Brunia points out the strong relation between anticipatory attention and motor preparation, and suggests that the reticular nucleus of the thalamus has a central role in both (Brunia, 1999). It has been shown that anticipated action mobilizes the ANS in accordance with how much effort is anticipated; and that uncertainty increases the amount of activation (Brunia, 1993). This supports our hypothesis of the link between attention and motor and autonomic state, suggesting the possibility (as claimed by the BTES) of altering muscle tension, posture and autonomic arousal by voluntary modulation of attention. Meditation has been studied primarily as an attentional strategy, and its positive effects on autonomic, affective and cognitive processes are well documented (Raffone and Srinivasan, 2010; Chen et al., 2012; Desbordes, 2012; Fox, 2012; Friese et al., 2012; Kox et al., 2012; Sedlmeier et al., 2012; Vollestad et al., 2012; Tang et al., 2014).

Expectation: Cognitive Response, Appraisal, Implicit Memory

The term "cognitive" can be ambiguous (Canamero, 1998). While it refers broadly to knowledge and awareness it may conflate different kinds of knowledge. It may confuse explicit fully conscious verbal and conceptual knowledge with implicit, emotional, non-verbal knowledge. This distinction has recently been explored by Stott (2007) as "rational-emotive dissociation." In memory research a clear distinction is made between explicit and implicit (Schacter et al., 1993). Explicit (autobiographical and episodic) memory can be brought into full consciousness, considered and re-evaluated. Implicit (including procedural) memory usually cannot, and is stored in different parts of the brain (Reber, 2013). Implicit memories influence behavior without one being conscious of this influence (Roediger, 1990). Procedural memory stores the action patterns associated with different situations and activities. The appraisal of events is largely based on memory (Glenberg, 1997). If that memory is explicit (subject to conscious thought and decision), we could term it explicit appraisal; if the memory is implicit it is implicit appraisal (Castelfranchi, 2000; Stott, 2007), or what Polanyi termed "tacit knowledge" (Polanyi, 1962).

Implicit and procedural memories are quickly activated and are accessed at a subcortical level (Roediger, 1990). They activate a set of expectations about the situation. Glenberg (1997) suggests that the main function of memory is to guide appropriate action (and therefore preparation for action) in the present moment. The simulation of bodily experienced states and actions are significantly involved in memory (Ross et al., 2007), understanding (Barsalou et al., 2003; Pulvermüller, 2005), interpersonal communication (Hostetter and Alibali, 2004), social interaction (Sebanz et al., 2006), and spatial perception (Tversky, 2003). This supports the idea that the expectancy aspects of the PS are intrinsically linked with affect and bodily preparedness.

Fully conscious appraisal involving explicit memory is slower, and comes after the rapid initial appraisal. Although cortical processing can and does modify the activity of the subcortical centers ("top-down"), the "bottom-up" connections are more extensive and arguably at least as powerful (Critchley, 2013). People frequently find themselves reacting and deciding "emotionally," often based on early implicit learning (Hovdestad and Kristiansen, 1996; Luethi et al., 2008; Orange, 2011). Appeals to "reason" concerning emotional reactions are often ineffective (Langer, 1975; Langer et al., 1978; Goleman, 2006; Goel, 2014). The theory of cognitive dissonance states that, once a certain set of expectations is in place, people tend to ignore disconfirming perceptions and notice confirming ones (Festinger, 1962).

Appraisal at a subcortical level has a direct and immediate effect on affective, visceral and motor function, and is not easily accessible to change (Critchley, 2013). Cortical (explicit) appraisal is easy to access consciously, fairly easy to change, but may not have much effect on emotion and autonomic state (van der Kolk, 2002).

We suggest that subcortical, implicit appraisal is a core aspect of the PS, to be distinguished from fully conscious rational appraisal. In this paper we will use the term "expectancy" or "expectation." We define this as a rapid, automatic, marginally conscious process of appraisal, accessing implicit and procedural memory and generating a set of expectations concerning the present situation. Porges' concept of "neuroception" (Porges, 2004) is an example of such a process. He postulates a largely unconscious, sub-cortically processed perception of the safety, or lack thereof, of the environment.

Categories of PS

The concept of PS leads to the question: what different kinds of PS are there? The early view of the ANS as bivalent (ergotropic and trophotropic) suggests two PSs: readiness for active mobilization, and preparedness for quiet recuperation.

Levine (1977) and Berntson (Berntson et al., 1994) have demonstrated that the parasympathetic and sympathetic branches are not limited to reciprocal activation, suggesting a range of possible states.

Porges' polyvagal theory suggests five states (based on combinations of dorsal vagal, sympathetic, and ventral vagal activity): immobility without fear (dorsal vagal) immobility with fear (dorsal vagal and sympathetic); fight-or-flight mobilization (sympathetic), play (sympathetic and ventral vagal), and social engagement (ventral vagal).

Panksepp defines seven core subcortical emotional circuits, each of which is neurologically and chemically distinct and has its own characteristic postural, affective, autonomic, attentional, and cognitive patterns: SEEKING, FEAR, ANGER, LUST, NURTURANCE, PLAY, GRIEF (Panksepp, 2011) (The use of capitals is Panksepp's way of distinguishing his proposed classification from the ordinary use of these words). This schema partly overlaps Porges', and could form the basis for a partial taxonomy of PSs. The instinctive appetitive drives such as hunger, thirst, and thermoregulation, could also define specific PSs. Our theory suggests that any of these PSs (a preparatory state oriented to escape, attack, sexual activity, exploration, nurturance, etc.) could become maladaptive through persistence or disorganization, and form the basis for various kinds of distress, not all of which would currently be termed "stress."

Stress and the PS

How is the PS relevant to stress, and how does this differ from the view that stress is excess sympathetic arousal? Cannon's (1939) and Selye's (1954) early theories of stress hypothesized a unitary "stress response" involving a series of automatic neurophysiological reactions: activation of the sympathetic and inhibition of the parasympathetic nervous systems, triggering of the adrenal medulla and cortex, the release of catecholamines and cortisol. More recent research reveals the complex modulation of this response in the face of different forms of physiological challenges (Saper, 2002), the complex dynamics of the interaction between sympathetic and parasympathetic branches of the ANS (Gellhorn, 1967b; Levine, 1977; Berntson et al., 1994), the interactions between the ANS, the immune system (Mignini et al., 2003), and other subcortical structures modulating arousal, attention, affect, motivation, and movement (Tucker et al., 2000; Öhman et al., 2000; Strominger et al., 2012; Leventhal, 2014; Norman et al., 2014), and the neurochemical details of allostatic load and overload (Seeman et al., 2001; Lupien et al., 2006), as well as the involvement of cortical structures in these subcortical processes (Berntson and Cacioppo, 2007). Despite these developments the single word "stress" continues to be used. To our knowledge, our hypothesis that stress can be understood in terms of preparation for action has not previously been proposed.

Stress is not a single phenomenon, and we believe that the use of the word in a scientific context is no longer justified. Instead we suggest that the broad range of phenomena subsumed under the term can be discussed in terms of whether the current PS is adaptive or maladaptive to the current situation. Some ambiguity may be involved, in that there could be more than one kind of response that might be adaptive in certain situations.

This framework allows the discussion of all the phenomena referred to as stress, the clarification of the five questions about stress raised above, and the discussion of a number of dysfunctional states not normally referred to as stress. In addition it allows the consideration of healthy and optimal responses. The discussion below focuses mainly on ergotropic and trophotropic PSs; we hypothesize that similar dynamics are involved in all PSs, but there is as yet little data to support this.

Adaptive PS

The simplest form of stress is sympathetic (ergotropic) arousal in a challenging situation: fight or flight. This is necessary, appropriate, and not problematic. In response to moderate acute challenge, there is a rapid increase in sympathetic activation accompanied by a decrease in parasympathetic activity. This ergotropic state facilitates vigorous response to the challenge. This is followed by a parasympathetic "rebound," and a return to baseline of the sympathetic activation (Gellhorn, 1956). This is usually referred to as acute stress (Everly and Lating, 2013). In PS terms, the adaptive PS leads to effective action, the situation is successfully resolved, and the PS of arousal subsides and is replaced by one of recuperation (trophotropic). This process occurs both in sudden threatening situations, and also in voluntary activities such as sports and risky recreation. This short-term activation of adaptive ergotropic PS has been called "good" stress (Everly and Lating, 2013). It usually leads to increased ability to handle stress: "stress inoculation" (Meichenbaum et al., 2009) or resilience (Karatsoreos, 2013; Wu et al., 2013). We hypothesize this involves an increased ability to adopt *and relinquish* PSs. This could be tested by observing whether exposure to successfully resolved moderate stress increases performance on a "stop signal" task (Logan, 1994) (which measures the ability to let go of expectations).

However, if the threatening situation is prolonged, negative neurophysiological consequences [allostatic overload (Lupien et al., 2006)] may occur despite the adaptive nature of the PS. This is one form of chronic stress, which can only be prevented by ending exposure to the challenging event. If the situation is very extreme, it may exceed the realistic capacities of the organism to cope. In this case, the PS may nevertheless remain coherent and organized, in which case there may be few lasting consequences once the event is over. Or the PS may become disorganized (competing PSs may be simultaneously aroused—see below for discussion), which increases the chance of post-traumatic stress (PTS) (Bovin et al., 2008) (See **Table 1**).

Maladaptive PS

We define four kinds of maladaptive PS; see **Table 2** below. First, the PS could be well-organized but not well matched to handling this particular situation. Second, the PS itself could be disorganized. In either case, the maladaptive PS may be "persistent" (a PS which arose in response to an earlier situation but has continued beyond its utility) or "situational" (a PS in response to the present situation which is not well adapted to handling that situation. By definition, a PS is organized to enable effective action. Once the action is successfully completed, the PS subsides. We suggest that one cause for a PS not subsiding (persisting) is the

TABLE 1 | Outcomes of adaptive PS in four situations.

PS	Action	Result	State of PS	End result
Adaptive PS in time-limited situation	Appropriate action taken	Resolution of situation	Release of PS	Formation of new PS. Increased Resilience
Adaptive PS in chronic situation	Appropriate actions taken	Situation not resolved quickly	Prolonged PS	Prolonged PS—Increased AL; possible eventual overwhelm
Adaptive PS in overwhelming situation	Appropriate actions taken	Situation overwhelming	PS stays organized	Once the situation ends, no PTS
Adaptive PS in overwhelming situation	Appropriate actions taken	Situation overwhelming	PS disorganizes: trauma	Once the situation ends, likely PTS

When the PS is well matched to the challenging situation (adaptive), there can be a variety of outcomes depending on the situation. If the situation is successfully resolved within a short time, there will be increased long-term resilience. If the situation fails to resolve quickly, there may be increased allostatic load. If the situation overwhelms the capacity to cope but the PS stays organized, there may be few long-term consequences. However if the PS becomes disorganized (see text for explanation) there may be lasting post-traumatic stress. (AL, allostatic load; PTS, post-traumatic stress.)

TABLE 2 | Two dimensions of maladaptive PS.

Maladaptive PS		
Situational	Organized	Disorganized
Persistent	Organized	Disorganized

Maladaptive PSs can be categorized in two dimensions. First, whether they have arisen in (poorly matched) response to the present situation, or whether they are chronic, persisting unresolved from a previous situation. Second, whether (despite being maladaptive) they are organized (retaining coherent goal organization), or whether they are disorganized (competing PSs arising simultaneously).

failure to complete the action pattern. Mandler's experiments on the interruption of organized behavior as a principal cause of anxiety and disorganized behavior are supportive of our suggestion (Mandler, 1964; Mandler and Watson, 1966).

Persistent PS

If ergotropic arousal [in Panksepp's terms, the FEAR and RAGE circuits (Panksepp, 2011)] persists long after the situation has passed, this is problematic. The PS does not end, and the organism continues to prepare for challenge. Ergotropic arousal is designed to handle time-limited challenges and has deleterious neural and neurochemical effects ("allopathic load") if sustained. Since the challenging situation is no longer present, action cannot be taken and the PS does not resolve (Mandler and Watson, 1966). This usually leads to decreased resilience as allopathic load increases (Seeman et al., 2001).

The question "what are the neurochemical details of allopathic load" is different from "what causes the PS (and thus the accumulation of allopathic load) to persist?" The PS perspective distinguishes the *effects* of "stress" from the actual nature of "*stress*" *itself*: the maladaptive PS. In our view, it is the ending of the maladaptive PS that ends the core stress response, not the correction of neuro-humoral imbalance or the removal of the challenging situation. (Of course, correcting neuro-humoral imbalance due to disease or genetics, and remedying the external situation, are crucial where possible.)

Gellhorn has shown in rats that a shock above a certain threshold of duration and intensity prevents the normal parasympathetic rebound, and the sympathetic system may remain activated indefinitely (persistent PS). He refers to this as "tuning" (Gellhorn, 1968). A similar phenomenon, heightened reactivity of the amygdala, is termed "kindling" (Cottrell and Nyakas, 2013). We suggest that both are examples of persistent PS.

If this hypothesis is correct, it would suggest that if the rat is given an opportunity to complete the PS in vigorous action, the PS would be released and the behavioral problems disappear. This has been shown to be the case. A rat alone in a cage may develop behavioral problems in response to shock; but if the rat is in a cage with another rat with which it can fight, it is much less likely to develop problems (Weinberg et al., 1980). In humans, subjects startled by a pistol shot but instructed not to move remained in a state of elevated sympathetic activation afterwards, but if encouraged to move vigorously their system returned to normal (Freeman and Pathman, 1942). If rats are subjected to shock but restrained from escaping, they develop behavioral problems (Mandler and Watson, 1966). If the rats are later placed in the original situation and given an opportunity to escape through vigorous action, the conditioned fear rapidly disappears (LeDoux and Gorman, 2001). We suggest this is because the PS is now given the opportunity to resolve and the action patterns can complete. These results suggest that if adequate ergotropic activity does not occur the ANS may not return to balance and the PS generated in response to the threat may persist. This supports our hypothesis that completing the action pattern of a PS ["biological completion" (Levine, 2010; Payne et al., 2015)] enables it to subside (See **Figure 2** for a summary).

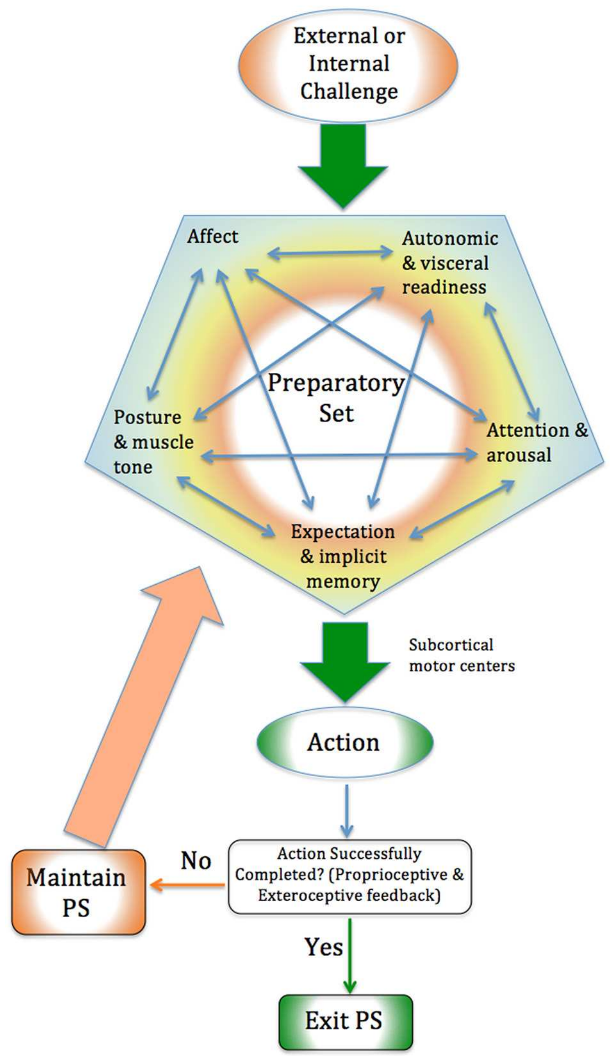

FIGURE 2 | Biological Completion In response to situational challenge, the PS prepares a response. If the preparation culminates in successful action, the PS can subside. If not, the PS may persist. Proprioceptive and exteroceptive sensory information informs the organism about the success or completion of the action.

Disorganized PS

If the threat is extreme, inescapable, or very prolonged, there may be an apparent "spillover" of activation from the ergotropic to the trophotropic systems, possibly due to spreading neural arousal from anterior to posterior hypothalamic nuclei (Gellhorn, 1967a). Several researchers have documented this phenomenon (Gellhorn, 1959, 1967a; Paton et al., 2006). It involves simultaneous high activation of sympathetic and parasympathetic systems and the loss of effective coping ["co-activation": see (Berntson et al., 1994)]. Such a reaction can be induced in animals by physically restraining them from escaping shock (Mandler and Watson, 1966; Shors et al., 1989; Amorapanth et al., 2000). This is the canonical way of inducing PTSD-like symptoms in animals. This response has been called tonic immobility (TI) (Hoagland, 1928; Bovin et al., 2014; Marx et al., 2008). TI and similar symptoms have been associated with increased likelihood of PTSD in humans, and develop under similar conditions of restraint (Suarez and Gallup, 1979; Volchan et al., 2011; TeBockhorst et al., 2015). TI prevents effective completion of the defensive response. Porges' polyvagal theory characterizes this fear-based immobility as a simultaneous activation of the sympathetic and the evolutionarily more primitive dorsal vagal system (Porges, 2001).We suggest this can be conceptualized in our framework as the simultaneous arising of mutually incompatible PSs (flight and freeze), which leads to a disorganized and ineffective response. We suggest that the ensuing "stress" and behavioral problems can be explained as the maladaptive persistence of the disorganized and interrupted PSs. This may provide an alternate way of viewing "dissociative" behavioral phenomena. The PS perspective suggests that resolution of these symptoms can come about by enabling the PSs to be released through completion of the action pattern. However, this resolution may not happen as readily in animals with TI as with sympathetically "tuned" animals: when animals with TI are placed again in the cage they may not spontaneously try to escape. The researcher may have to physically move them to safety before the instinctive defensive action will take place (Gellhorn, 1967c), indicating a clear distinction between what we are calling "organized" and "disorganized" PS. Our theory suggests that in such cases two contradictory PSs must be released before resolution can take place: the escape and the immobility. This suggests greater clinical difficulty in dealing with the latter, which is widely recognized to be the case. See **Table 3** for further discussion, see below under Biological Completion, also (Levine and Buczynski, 2013; Payne et al., 2015).

Varieties of "Stress"

As discussed above, one advantage of the PS framework is that it enables identification of a wide range of specific dysfunctional conditions. These conditions may be referred to collectively as "stress," even though they are quite distinct; or they may be excluded from this category despite the fact that it would not be true to claim they are "not stressful." We suggest that *any* maladaptive PS, is problematic for the organism, not only ergotropic PS involving anger and fear. We suggest that different maladaptive PSs will have discrete harmful consequences on all levels from physiological to psychological. Animal experiments aimed at frustrating specific drives could test this.

We further suggest that our model of disorganized PSs could apply more broadly than in the above example of conflicting immobility and escape impulses. We suggest it might be possible for extreme activation of any PS to spread into another, competing PS, and cause disorganization and ensuing behavioral problems. In animals, this could be tested through direct brain stimulation.

Following Panksepp's model of seven primary emotional states, each with its own neural and neuro-chemical substrate (Panksepp, 2011), we suggest that a persistent FEAR PS will have different neurochemical, neural, and psychological consequences from a persistent RAGE PS. Likewise, the intrusion of a NURTURANCE PS into a situation that requires RAGE, a LUST PS when NURTURANCE is required, a GRIEF PS when SEEKING is required, each will have different negative consequences, each with a distinct profile. It is hardly useful to call them all "stress," nor to debate which constitute "stress" and which not. We believe the PS framework offers a more precise and nuanced way of characterizing a wide variety of problems, and could guide targeted therapeutic approaches. Bos and Panksepp have already used a similar framework to suggest novel pharmaceutical approaches to different forms of stress (Bos et al., 2012). The identification of the specific PS involved in particular forms of emotional or autonomic dysfunction could guide effective intervention via BTES or cognitive-behavioral therapies. A nuanced understanding of

TABLE 3 | Four kinds of maladaptive response and treatments suggested by PS view.

PS	Organized/disorganized	Reason for maladaptation: Situational or persistent	PS perspective on effective treatment
Maladaptive PS	Organized PS	Faulty subcortical appraisal of present situation (situational)	Reappraisal through awareness of PS—voluntary re-organization
	Organized PS	Held over from a previous unresolved situation (persistent)	Resolution or release of previous situation
	Disorganized PS	Overwhelmed by present situation (situational)	Trauma first aid and treatment needed
	Disorganized PS	Overwhelmed by previous unresolved situation (persistent)	PTSD or DESNOS: Resolution of past trauma needed

The PS perspective suggests that the four kinds of maladaptive PS (organized/situational, organized/persistent, disorganized/situational, disorganized/persistent) each call for a different therapeutic response. If the PS is well organized and arises in response to the current situation, but is poorly matched, a process of conscious re-organization may be effective. A well-organized but persistent maladaptive PS could be termed a "bad habit"; a resolution through increased awareness of the origins of the PS may help. If the PS is disorganized, and the direct result of the present situation, immediate trauma "first aid" may be very effective. If on the other hand the disorganized PS is the result of past unresolved experiences, PTSD or "disorders of extreme stress not otherwise specified" (DESNOS) may follow, which require specific trauma-oriented therapy. DESNOS is a term from DSM V which covers a variety of trauma sequelae which fail to fall into the category of PTSD. (DESNOS: Disorders of Extreme Stress Not Otherwise Specified) maladaptive PS, could increase the effectiveness of a wide range of medical diagnoses and interventions.

Five Questions about Stress

Below we restate the five questions about stress posed at the beginning of the paper, and indicate briefly how the PS perspective can clarify them. Many of these issues have already been addressed above and are summarized below.

"Good" stress/"bad" stress

The mobilization of organismic resources in response to challenge is necessary and beneficial, and yet under some circumstances mobilization can lead to significant problems. A distinction has been made between "good" stress and "bad" stress (Selye, 1985), but the exact nature of the difference between them is not clear. The PS perspective distinguishes adaptive and maladaptive PSs; the former generally lead to greater resilience ("good" stress), the latter to various harmful consequences ("bad" stress).

Acute, chronic, and traumatic stress

Stress has been classified as acute, chronic and traumatic. This classification has been made on the basis of differing neurophysiological reactions (Everly and Lating, 2013); but it remains unclear what determines these differing responses. The PS perspective suggests that acute stress involves an appropriate, time-limited PS appropriate to threat or challenge (mobilization of active resources); chronic stress involves either a persistent maladaptive PS or adaptive response to prolonged challenge; and traumatic stress involves a disorganized PS characterized by regression to a phylogenetically more primitive (Porges, 1995) form of PS (Halvorsen, 2014).

What is resilience?

It is widely recognized that different people exposed to almost identical events can respond in very different ways. It has been shown that the presence or lack of resilience may be due to genetic factors, adverse childhood experience, and personality make-up (Karatsoreos, 2013). However, there is little clarity about exactly what this resilience *is*.

The PS perspective suggests that resilience is in part the ability to let go of inappropriate PSs and to adopt functionally appropriate ones. Adverse childhood experience may cause persistent maladaptive PSs, and some measures of personality associated with poor resilience may be measures of maladaptive persistent PSs. We suggests that resilience may be improved by ending persistent maladaptive PSs as well as by learning new adaptive ones. We also suggest that cognitive techniques will be effective only to the degree they influence subcortical organization (van der Kolk, 2002). This suggests the value of methods (such as those used by BTES) which more directly affect subcortical areas.

Appraisal and expectation

A distinction has been made between physical and physiological stressors (such as cold or toxin) and psycho-social stressors (such as a challenging social situation or a negative thought) (Everly and Lating, 2013). In the latter, the person's appraisal (and consequent expectations) of the situation is regarded as largely determining the response (Olff et al., 2005). However, the organism's response even to physical stressors can be altered voluntarily. For instance Hof and volunteers trained by him have been studied for their anomalous physiological responses to extremes of cold exposure and inflammatory challenge (Gard et al., 2014; Riley and Park, 2014). A significant part of this training involves the re-appraisal of the nature of cold as well as BTES techniques of breath control, posture and imagery (Kox et al., 2012, 2014).

On the other hand the concept of the "appraisal" of a psychosocial stressor is not clear. The mere thought that a situation will not be stressful is unlikely to change a person's response; and yet the previous examples, as well as the proven effects of cognitive restructuring therapy, show that appraisal can have a significant impact. Why should appraisal sometimes appear to determine outcome and at other times not?

The PS perspective suggests that re-appraisal occurring only on a verbal/conceptual level is less likely to alter the PS, and thus the stress response; but altered subcortical expectations may be more effective. This suggests that attention to interoceptive and proprioceptive experience may be more effective in handling stress than attention to ideas and thoughts alone, because bodily experience enables more direct access to the PS.

What is the stress response itself?

Recent work on "allostatic load" (Cicchetti, 2011), the accumulated "wear and tear" from continual adjustment to changing life conditions, has provided detailed knowledge about the neurochemical and neuroplastic *effects* of stress. In our view, this still leaves unaddressed the core of what the stress response itself *is* and how it can best be changed.

The PS perspective suggests that the essence of the stress response is the perpetuation of maladaptive PSs, and that effective treatment of stress should involve a focus on changing subcortical preparatory organization. The BTES offer methods with this focus.

BTES

What are BTES and How Do They Relate to PS?

BTES present a specific challenge to the scientific investigation of human suffering and its remediation. Traditional science has been based on the Cartesian dualism of mind and body (Damasio, 2005), whereas the BTES are firmly based in a non-Cartesian view. Despite the current interest in "mind-body medicine," this paradigm persists, as does the continuing gulf between the BTES and mainstream medical and psychiatric theory (Leder, 1992). In presenting the PS as an explanatory framework we hope to demonstrate that current neuroscience supports the view of the BTES that bodily aspects (movement, posture, proprioception, interoception) are, at a basic level, inseparable from affective and cognitive aspects of the organism.

Defining BTES

We define BTES as a diverse group of educational and therapeutic practices, of traditional Asian and modern Western origin, which share a common set of assumptions and practices. They encourage attention to posture, breathing, movement, and proprioceptive and interoceptive sensation, as well as tactile and spatial awareness; and they use this bodily attention as well as voluntary movement and imagery as the principal means to accomplish therapeutic change (Read and Stoll, 2009). They do not deny "disease," but do not use a disease framework in evaluation or treatment (This distinction can be a central issue in studies of efficacy related to medically defined disease states.). Importantly, BTES do not make a fundamental distinction between body and mind, tending to regard them as poles on a continuum rather than fundamentally different realms (Rosenthal, 1991). Our hypothesis is that the PS is an integrated subcortical state that is significant in physical and emotional distress, and that interventions on any one of its components will tend to alter all the components. Further, that BTES interventions are based on this view; see **Table 4**. At the end of this article we summarize the suggestions we have made for testing these hypotheses.

BTES are normative

BTES aim to increase overall human health, physical, emotional and mental, toward optimal functioning, and not only to remedy ill health. They all include the concept of an optimal state which maximizes adaptive ability across a wide range of situations. This is generally defined (Johnson, 1995, 1996) as a state that is flexible, balanced, open, and capable of adjusting quickly to the varying demands of the environment. Such a state allows the rapid adoption of specific adaptive PSs as well as the ability to quickly relinquish them. It is variously described as involving proprioceptive experiences of balance, stability, and lightness (Jones, 1976); an open flexible attention (Brown and Ryan, 2003); interoceptive experiences of calm, warmth, and flow (Csikszentmihalyi, 2008); flexible expectations (Farb, 2012); and affective feelings of openness, confidence and curiosity (Ekman et al., 2005). BTES claim that optimal PS is quite rare, that most people are stuck in maladaptive PSs.

Changing PS

We have suggested that stress can be resolved by releasing the maladaptive PS, and that this is the primary aim of BTES. A broad examination of the BTES suggests that there are two principal ways PSs can be changed. The first is by becoming conscious of the process of maintaining the PS, voluntarily letting go of it and replacing it by a more adaptive PS. The second is through "biological completion," in which the originally obstructed impulse is enabled, in a safe context, to complete itself.

Awareness of PS

Both of these processes, voluntarily letting go of a maladaptive PS and biological completion, require awareness of the PS. Since PS are primarily sub-cortical, it may not be easy for a person to be fully, reflectively aware of their PSs, especially in the case of persistent maladaptive PS. BTES claim that this lack of awareness is the major obstacle to being able to let go of the PS, and that by cultivating the capacity to attend to subtle aspects of proprioception and interoception (as well as attentional orientation and affective state) it is possible to become aware of the PS and of one's active (if involuntary) process of adopting and maintaining it.

Damasio's theory of somatic markers (Damasio et al., 1996; Damasio and Carvalho, 2013) emphasizes the important role of interoceptive awareness in becoming aware of one's inner state. Interoception enables one to become aware of the (autonomic) state of the body, and is strongly related to emotional response and affective and visceral aspects of the PS. Craig and Critchley (Critchley et al., 2004; Hölzl et al., 2009; Garfinkel et al., 2013; Sel, 2014), as well as earlier researchers (Newman, 1974; Mogenson et al., 1980), have suggested the neural pathways for this mechanism. The anterior insula and anterior cingulate cortex are where this information reaches full awareness. Proprioceptive and kinesthetic information likewise bring to consciousness other essential aspects of the PS including posture, muscle tone, and movement preparation (Suetterlin and Sayer, 2013). The cortex receives this information in the sensorimotor, pre-motor and supplementary motor cortexes (Gellhorn, 1964; Prochazka, 2011)

TABLE 4 | Use of PS in BTES.

BTES	References	Components of PS				
		Posture/tone	Autonomic	Affect	Attention	Expectation
Qigong	Cohen, 1999	P	P	P	P	P
Yoga	Satchidananda, 1978; Sivananda, 2005; Singleton and Byrne, 2008; Jois, 2010	P	P	C	P	P
Meditation	Johnson, 2000; Frantzis, 2001; Kabat-Zinn, 2005; Dorjee, 2013	P	C	C	P	P
Alexander	Jones, 1976; Alexander and Maisel, 1989; Gelb, 1995	P	C	C	P	P
Feldenkrais	Feldenkrais, 2002, 2005; Rywerant and Feldenkrais, 2003	P	C	C	P	C
Rolfing	Rolf, 1989; Sise, 2005; Karrasch, 2009	P	C	C	P	C
Reichian	Boadella, 1974	P	P	P	C	P
Formative	Keleman, 1971, 1979, 2013	P	P	P	P	P
SE	Levine, 1997, 2010; Payne et al., 2015	P	P	P	P	P

The listed BTES use interventions that involve several of the components of the PS. Stated claims of influencing other components of the PS are also listed. Although the BTES differ in emphasis and in the details of the intervention, they share a similar framework. The references in this table are to substantiate that the BTES claim to use these forms of intervention and to have these effects; they refer mainly to the writings of the founders or prominent practitioners, not to peer-reviewed publications. Key: P, Principal form of intervention C, Effect claimed.

as well as in the body schema area in the inferior parietal and extra-striate body area (Arzy et al., 2006; Daprati et al., 2010; Ionta et al., 2011). Proprioceptive and kinesthetic feedback bring information from the basic and EMS (Holstege et al., 1996), and thus can inform the conscious mind about unintended automatic or emotionally driven motion, bringing information about current PS.

Voluntary change

The BTES claim that once awareness has been achieved it is possible to alter the PS through the use of the following voluntary procedures:

- Proprioceptive or interoceptive imagery;
- Affective imagery;
- Adopting a specific posture;
- Performing specific movements;
- Breathing in certain patterns;
- Paying attention in certain ways;
- Modulating expectation/appraisal.

As indicated above, there is evidence for the effectiveness of each of these in altering stress responses. We suggest that the anterior cingulate (ACC) and the premotor cortex (PMC), as well as portions of the orbito-frontal cortex (OFC), are the principal originations of these actions. It has already been shown that ACC has significant effects on amygdala (Posner et al., 2007) and other subcortical autonomic, affective and motor areas (Critchley et al., 2005), as well being involved with acts of intention (Shenhav et al., 2013). PMC has rich connections to subcortical motor centers, alters posture, muscle tone and autonomic state (Jeannerod, 1994; Desmurget and Sirigu, 2009). OFC likewise has extensive connections to subcortical areas and is central to several executive networks (Price, 2007)}. It has been shown that both motor (Collet and Guillot, 2010; Anema and Dijkerman, 2013) and affective (Lang, 1979) imagery can alter subcortical activity.

Biological completion

In our discussion of maladaptive PS above, we referred to "biological completion." This involves the completion, through imagery or safe re-enactment, of the impulses of the persistent maladaptive PS. Several forms of BTES use this approach, especially the more psychotherapeutically oriented ones. The term itself comes from Somatic Experiencing (SE), but many other BTES use methods others use methods which may involve this mechanism. This includes body-oriented therapies generally. Movement practices such as Spontaneous Qigong (Cohen, 1999), Kriya and Tandava Yoga (Odier, 2003), and T'ai Chi, may involve similar processes. Clinical experience in SE shows that biological completion often involves autonomic discharge such as trembling, flushing, or crying (Levine, 2010; Payne et al., 2015) which appear to result in a normalization of autonomic activity. These processes have been very little studied, although Gračanin (2014) has demonstrated that crying can facilitate autonomic and affective balance, and trembling, which has been documented during TI in response to rape (Suarez and Gallup, 1979), may be the beginning of such a discharge (Payne et al., 2015). Facilitating the completion of the defensive reaction, in a safe therapeutic context, restores balanced functioning to the ANS and the network of core subcortical centers, resolves the stress response, and allows the patient to let go of the trauma-oriented PS in which they had been stuck since the precipitating event. This completion happens through the use of imagery and subtle movement to enact a successful resolution of the situation. Biological completion is discussed at greater length in Payne et al. (2015) and Levine (2010).

We believe there is supportive evidence for this process; as mentioned above, of restrained animals recovering from trauma through completion of the escape response, as well as the role of TI in PTSD in humans. However this theory is still speculative. Systematized manualized application of this procedure in randomized controlled trials, with measurement of affective and autonomic variables, would help to clarify the impact of biological completion as compared with cognitive-behavioral and exposure therapies. It should be determined whether generalized vigorous movements have the same effect as specific completion of the movements involved in the original traumatic situation. In rats this might be tested by shocking and restraining the rat in a situation requiring a given response, then later offering some of the rats an opportunity to complete that response (e.g., running to safety), while offering others a quite different activity (such as climbing to get food). The biological completion hypothesis would suggest that the former group would recover more completely than the latter.

Research on BTES

Seated meditation (Raffone and Srinivasan, 2010; Travis and Shear, 2010; Holzel et al., 2011a) and Yoga (Gard et al., 2014) have received the most research attention, with Qigong (Jahnke et al., 2010; Payne and Crane-Godreau, 2013) a close third. Somatics and body psychotherapy have has the least research reported, although clinical and anecdotal evidence for their efficacy is evidenced by informal published accounts, the authors' experience, and personal communications from practitioners. Given their promise to support and optimize health, we hope our proposed framework might facilitate research into their mechanisms. Research into Somatics particularly has been hampered by poor quality of experimental design, inadequate controls, small study size, poorly standardized interventions and most significantly for our paper, a lack of full understanding on the part of researchers of the concepts and techniques of BTES (Kerr, 2002). See for instance this study contrasting the philosophical approaches of the Feldenkrais Method and conventional exercise (Wright, 2000).

Examples of BTES

A complete survey of all forms of BTES is well beyond the scope of this paper. We will confine our discussion to several of the better-known systems. BTES fall into three broad categories:

- Modern forms of traditional Asian psychophysical practices. In this category we will discuss Qigong and Yoga as well as seated meditation.
- Somatics. This term refers to a variety of educational and therapeutic methods of recent (20th century) Western origin;

here we will discuss the Alexander Technique, the Feldenkrais Method, Continuum, and Rolfing.
- Western forms of "body psychotherapy." We will discuss Reichian Therapy and its off-shoots Bioenergetics, Formative Psychology, and Levine's Somatic Experiencing trauma therapy.

Modern Forms of Traditional Asian Psychophysical Practices

Qigong and Taijiquan

"Meditative movement" (MM) has been proposed as a term referring to a broad range of Asian contemplative practices (Larkey et al., 2009) including Yoga, Qigong ("Chi Kung") and Taijiquan ("Tai Chi"). There are however significant differences between Yoga and Qigong, so we will discuss them separately.

Qigong teaches balanced standing and movement accompanied by spatial, proprioceptive and interoceptive awareness (Cohen, 1999). It brings conscious awareness to the (mechanical) postural processes of grounding, orientation, and correct relation of the longitudinal axis to gravity (Cohen, 2012), thus promoting optimal postural preparedness and a sense of self-efficacy; and through the monitoring of breathing and other interoceptive information, muscle tone and movement (proprioception), and thought activity, brings about a calm, centered state in which one is responding to the actual present condition rather than preparing for past or future events. Further, it trains one to let go of inappropriate anticipatory tension, to maintain resilient flexible posture with balanced muscle tone, and to maintain this balanced preparatory state while moving in simple or complex ways, moving with a partner, or even simulating attack and defense (Diepersloot, 1997). One of the great benefits of martial forms of Qigong (like Taijiquan) is that it teaches one to prepare for extreme challenge by remaining flexible, grounded and aware rather than tensing in fear or anger or collapsing in fear. Although Qigong practice may not specifically address past traumatic memories, we suggest it may facilitate processing such memories by retraining the dysfunctional PSs associated with them. Qigong practice characteristically involves using imagined movement to create very subtle changes in bodily posture and proprioceptive experience. This engages the premotor areas (Gerardin et al., 2000), central to our concept of the PS. The methods of Qigong are fully congruent with our hypotheses concerning the PS.

Research into Qigong has been hampered by poor experimental design, small studies, and difficulty translating the traditional theory into scientific terms; for a discussion, see (Kerr, 2002; Payne and Crane-Godreau, 2013). However most studies point to positive results in a wide range of physical and psychological conditions, in some cases even when compared to standard treatments (Ng and Tsang, 2009; Jahnke et al., 2010; Lee et al., 2011).

Yoga

Yoga has been shown to be of benefit in a wide variety of conditions, and its literature is quite extensive. For a recent review, including extensive speculation on mechanisms, see Gard (Gard et al., 2014). Hatha Yoga (the principle form of Yoga practiced in the West) uses specific postures, often held for periods of time, to stretch and strengthen the body and to focus the mind (Iyengar, 1966; Singleton and Byrne, 2008; Jois, 2010). In our theory, persistent PSs will involve chronic muscle tension. It is widely accepted in Yoga and the manual therapies that chronic muscle tension results in a shortening of the fascia (Chaitow, 2010). Yoga postures restore appropriate length and alignment to the musculoskeletal structure, which may provide a new proprioceptive experience which may in turn help establish more flexible PSs. Carney's research supports the effect of posture on affect and neurochemical secretion (Carney et al., 2010). Yoga also uses breath control to alter the autonomic state (Brown and Gerbarg, 2005a,b) as well as the control of the attention. Yoga explicitly aims at establishing a more optimal overall psychophysical state (Jois, 1999). This is consistent with our hypothesis that Yoga addresses the PS through intervention on its components.

Meditation

Meditation, in particular "mindfulness" meditation from the Buddhist tradition, has been studied extensively. However, the focus has been mostly on cognitive and attentional aspects of meditation (Raffone and Srinivasan, 2010; Travis and Shear, 2010; Holzel et al., 2011a). A distinction has been made between static seated meditation (such as the traditional Buddhist Shamata/Vipassana practices) and "movement meditations," such as traditional Chinese Taijiquan (Larkey et al., 2009). While it is true that some forms of meditation emphasize primarily cognitive processes, the emphasis on posture in meditation is so widespread and so basic that this distinction must be questioned. In this paper we include seated meditation in the BTES category unless it places *no* significant emphasis on posture, breathing or physical sensation.

Although some authors have looked at the body awareness cultivated in some forms of meditation (Kerr et al., 2013), a crucial aspect has been almost completely ignored in the literature: posture. In almost all traditional systems of meditation, correct posture is stressed as an absolutely essential component (Johnson, 1996). In seated meditation, upright balanced posture is intrinsic to the meditative attitude (Johnson, 2000). We suggest that meditative awareness is a specific PS. In mindfulness, one prepares to meet each new experience without grasping, without shrinking away, but with flexible open presence, a balanced posture of mind, body and emotion. We believe meditation can be understood as a PS, a specific state of preparedness characterized by the absence of fixed maladaptive PSs.

Somatic Approaches

Alexander technique

The Alexander Technique (AT), developed by F.M. Alexander in the early 20th century (Alexander and McGowan, 1997), is a method for changing habitual patterns of posture and movement, and claims far-reaching effects on physical and psychological health. It points to the prevalence of poor habit patterns, but goes beyond a purely physical focus to define these faulty habits as "poor use of the self"; the self is defined as "the entire psycho-physical organism" (Alexander and Maisel, 1989). These unconscious patterns of behavior involve attention, thought and emotion as well as the body The principal method involves helping the student to become aware of their subtle preparatory physical and mental tensions; learning to pause and to "inhibit" these tensions; and then to complete the desired movement without the interfering tensions (Alexander and Maisel, 1989). This is a clear example of working with the PS; Jones, a student of Alexander's published a book summarizing his early investigations of the AT as producing change through the inhibition of postural sets (Jones, 1976). Jones makes it clear that the "postural set" is not the simple adoption of a physical posture, but an integrated change in attitude involving attentional, cognitive and affective components, largely equivalent to our concept of the PS. The "inhibition" referred to by Jones and Alexander is the process of relinquishing chronic maladaptive sets, very similar to the process we discuss above under Changing PS. Jones documents the increased mechanical efficiency of movement (using stroboscopic photography) as well as the subjective experiences of lightness, height and smoothness (in a questionnaire given to new students) (Jones, 1976). Extensive anecdotal and informal written accounts, as well as one of the authors' clinical experience, suggests that students also experience positive changes in physical and emotional health and improved cognitive function, consistent with our view that the PS links motor, affective and cognitive functioning.

There have been few scientific studies of the AT. It has been shown to be more effective than massage in treating back pain (Little et al., 2008), to increase functional reach (Dennis, 1999), to benefit patients with Parkinson's disease (Stallibrass et al., 2002), asthma (Dennis and Cates, 2000), and performance anxiety (Urbanski, 2012); for general reviews, see (Ernst and Canter, 2004; Jain et al., 2004). Stuart offers an interesting discussion of the AT and neurophenomenology (Stuart, 2013).

Feldenkrais Method

Strongly influenced by the AT, the Feldenkrais Method (FM) uses either complex movements guided by verbal instruction (Awareness through Movement) (Feldenkrais, 1990) or passive manipulation of the body by an instructor (Functional Integration) (Rywerant and Feldenkrais, 2003). It emphasizes proprioceptive awareness, fine motor discrimination, and the use of imagined movement. The stated aim is to offer the motor nervous systems a wider range of alternatives for movement, removing the constraints of limited habit patterns; the assumption is that the nervous system will then automatically choose the most efficient alternatives. Feldenkrais believes these changes will positively affect emotional and cognitive state; his theories are congruent with our hypothesis of the PS. Extensive anecdotal evidence supports this claim although there are only a few published studies. Most studies have positive results (Gutman et al., 1977; James et al., 1998; Lundblad et al., 1999; Kolt and McConville, 2000; Gomes and Vieira, 2013; Ramli et al., 2013; Pugh and Williams, 2014), although they are generally of poor quality.

A study of the use of language in the teaching of physical education versus the FM provides an interesting perspective on the differing world-views of BTES and conventional physical education (Wright, 2000).

Rolfing

Rolfing adopts a point of view similar to that of AT and FM, that physical structure and movement are foundational to well-being and have intrinsic links to autonomic, affective, cognitive and attentional aspects of the person (Rolf, 1977). This is congruent with our hypothesis. Rolfing uses deep massage on the connective tissue to undo the effects of chronic patterns of poor posture and movement (Larson, 1990). In an extensive but non-scientific literature, participants report substantial alterations in proprioceptive and interoceptive experience that affect their emotional and mental state, including transformative emotional releases and spontaneous re-evaluations of past trauma (Fahey, 1989; Karrasch, 2009). We suggest that the altered proprioceptive feedback from the muscles, and the newly available freedom of movement, may alter PSs and allow the subject to have a different "attitude" toward life; an attitude with affective and cognitive repercussions. This hypothesis is similar to the stated theory of Rolfing (Fahey, 1989; Sise, 2005).

There has been little scientific research on Rolfing. Studies are of poor quality and point to the need for more research and for the development of appropriate outcome measures. Studies have shown positive effects on balance (Findley et al., 2004), parasympathetic tone and pelvic angle (Cottingham et al., 1988) and neck pain (James et al., 2009), but no effect was shown on cerebral palsy based on measures of limb range of movement and gait velocity and efficiency (Perry et al., 1981).

Body Psychotherapy

Body-oriented psychotherapy pre-dates the development of verbal psychotherapies. Freud's mentor Pierre Janet first formulated and practiced body-oriented psychotherapy, using massage, breathing techniques, and guided movement to encourage the release of emotional blockages (Boadella, 1859). Freud initially used these techniques, but later abandoned them to focus on cognitive insight and the working through of the relationship between therapist and patient. Freud's student Reich continued to develop body-oriented psychotherapy (Boadella, 1974), and strongly influenced later methods (Boadella, 1976).

There has been little scientific research on body psychotherapy. There have been studies (more in Europe than in the States) which confirm its effectiveness for severe mental disorders (Ventling, 2002; Price et al., 2007, 2012; Levy Berg et al., 2009; Röhricht, 2014). Surprisingly, there has been little investigation into its mechanisms, although current neuropsychology seems to offer supportive and suggestive evidence. For a good survey of the field see (Heller, 2012). Exposure therapy may share some of the mechanisms of body psychotherapy, although the theory behind it is quite different (McNally, 2007).

Reichian Therapy

Reichian Therapy maintains that dysfunctional emotional/cognitive patterns are embodied in patterns of muscular tension ("character armor") (Boadella, 1974). In addition to insight techniques, Reich used massage, breathing exercises and guided movement to release the tensions. He believed that the tension patterns served to hold back instinctive emotional, physical and sexual impulses, blocking the natural charge/discharge process of the body (Boadella, 1974). The holding patterns identified by Reich are very similar to our concept of maladaptive persistent PSs: the restraint of instinctive responses may lead to a failure of the PS to subside and its persistence as a maladaptive pattern. Note that in our discussion of types of PS above, we suggest that *any* of the core emotional patterns (described by Panksepp) may lead to maladaptive PSs, including sexual responses and nurture-oriented impulses as well as the more familiar fear and rage responses. Reich's idea of health as a flexible state in which impulses are not chronically suppressed but allowed healthy expression is congruent with our suggestion that stress can be alleviated by the release of persistent and disorganized PSs.

In his later years Reich brought elements into his approach which eventually drew legal action from the government; his books were burned and he ended his life in prison. His successors have avoided these extremes, and have developed the embodied aspects of his approach, discarding the more analytical Freudian legacy.

Formative Psychology

Stanley Keleman's Formative Psychology (Keleman, 1979) is a sophisticated refinement of Reich's approach. Keleman emphasizes the use of conscious voluntary effort in forming ones attitude toward life and life events. "Forming" is not a metaphor, but literally the adopting of a certain shape; flexing or extending, shrinking or inflating, altering both musculo-skeletal configuration as well as visceral tone. According to Keleman, problems arise when, through early childhood events, we get "stuck" in a certain shape (Keleman, 1971); we adopt a fixed, maladaptive attitude toward life, which may be automatic and unconscious, inaccessible for modification. Keleman draws the attention of his clients to "how they do that," to the proprioceptive, interoceptive and kinesthetic subtle cues through which they can recover awareness of the original action, and make a voluntary choice to un-do it and to form oneself in a more functional way (Keleman, 2013). His approach is thus very similar to our hypothesis of the PS.

Somatic Experiencing

Peter A. Levine, is a PhD in psychology and psychophysiology, trained as a body psychotherapist and as a Rolfer. He developed Somatic Experiencing, a form of psycho-physical therapy specifically designed to resolve the effects of traumatic stress. He noted that animals in the wild, subject to extremes of stress, may exhibit freeze or collapse behavior similar to that of humans with PTSD (Hoagland, 1928; Nijenhuis et al., 1998). This has been documented as TI (Volchan et al., 2011). In animals this state seemed to generally be time-limited; the animal would go through an apparent physical "discharge" process, involving heavy breathing, shaking or trembling, and subtle locomotor motions; after which they appeared to have thrown off the effects of the stress (Levine and Buczynski, 2013). These naturalistic observations have not yet been documented in the literature but have been recorded on film by wildlife biologists (Lipscomb, 1982). SE addresses PTS by guiding the client to become aware, through interoception and proprioception, of unresolved defensive impulses, and then releasing these impulses through biological completion, described above.

The theories of SE are congruent with the PS framework, and the PS framework provides an explanation for the potential effectiveness of SE. Its methods and theory are discussed in Payne et al. (2015). Peer-reviewed research publications into the efficacy of SE methods are as yet limited to special applications of SE (See Payne et al., 2015–Corrigendum). Its methods and theory are discussed in Payne et al. (2015).

Suggestions for Further Research

Our hypothesis is that the five aspects of the PS–posture, autonomic state, affective state, attention, and expectation—tend to co-vary, suggesting a central integrated response we term the PS. Further, that the BTES involve changing one or more of these with the aim of changing the others too, bringing about a reorganization of PS, a more adaptive state of the organism, and a reduction of physiological and psychological markers of excess ergotropic activity (the most common usage of the term "stress").

There are readily available means for measuring the five aspects of the PS:

- Autonomic state: heart rate, breath rate, blood pressure, heart rate variability, galvanic skin response, as well as a number of biochemical markers such as C-reactive protein, catecholamine and steroid hormone levels.
- Affective state: any of a number of questionnaires. Both autonomic and affective reactivity may be tested using picture-viewing procedures accompanied by autonomic and affective measures (Lang et al., 1993).
- Expectation may be tested in several ways, including subliminal word perception threshold (Marcel, 1983).
- Attention could be tested with breadth-of-field experiments, gaze direction monitoring, flicker-fusion and word- or image-recognition threshold tests; such tests have already been used in evaluating the effects of meditation (Brown et al., 1984).
- Objective measurements of the kind of postural changes relevant to this context could include strobe photography (to measure the efficiency of simple movement patterns) (Jones, 1976), electromyography (to measure tension in selected muscle groups), and the use of moiré patterns to measure subtle changes in postural alignment (Meadows et al., 1970; Gertzbein et al., 1985).

A randomized controlled study could evaluate BTES interventions on one of these variables by using the other variables as outcome measures. We would suggest the use of an attention control group as well as an active control using a standard intervention such as relaxation or Cognitive therapy.

For example, one could monitor autonomic reactivity to a challenge such as picture viewing (Lang et al., 1993), and determine whether the guidance by a teacher of Qigong or the Alexander technique into a "centered" postures would bring about an alteration in reactivity, in comparison to a control activity or to a self-adopted posture. Further, one could determine whether this same postural guidance also brought about a widening of peripheral attention, a more positive set of expectations, and a more positive affective state, as our hypothesis would suggest. Similar experiments could be done with a BTES intervention on autonomic state (using controlled breathing), affective state (using methods from body psychotherapy), attention, or expectation.

Our hypothesis that the neural substructures involved in the PS are largely sub-cortical is more challenging to verify in humans, as it is technically demanding to monitor subcortical activity in humans since it is situated deep in the brain. Panksepp makes a case for the validity of generalizing from animal data to humans (Panksepp, 2011). fMRI studies of humans undergoing BTES procedures are possible in some cases, although hampered by the limitations the fMRI procedure places on movement. Pre-post-procedure fMRIs would yield useful data on subcortical changes following BTES interventions.

As noted in several places above, experiments of this sort have already been done with results suggesting support of our hypotheses.

Summary

Here we have proposed that the concept of the PS as an important but underemphasized phase of the organism's response to challenge. The PS is an integrated, largely sub-cortical, organization of the organism in readiness to handle events. We suggest that the PS may persist inappropriately or become disorganized in states of chronic or traumatic stress, and that intervention through attention to interoceptive and proprioceptive experience is more likely to be an effective therapeutic approach than one focused on verbal meaning. We have laid out the various aspects of the PS—movement, posture, orientation, autonomic state, emotion, expectation—and the neurological substrates of each. We suggest that since the PS is primarily subcortical, it is quicker and more fundamental, and may override or bias cortical executive function. We have presented a brief overview of various forms of BTES, and suggest that they share an approach very similar to the one we present with the PS framework, and that the PS framework therefore offers a way of approaching the neuroscience of the BTES. We hope that our suggestions facilitate further research and integration of these concepts that have application into virtually all aspects of human health and well-being.

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Potential self-regulatory mechanisms of yoga for psychological health

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Research suggesting the beneficial effects of yoga on myriad aspects of psychological health has proliferated in recent years, yet there is currently no overarching framework by which to understand yoga's potential beneficial effects. Here we provide a theoretical framework and systems-based network model of yoga that focuses on integration of top-down and bottom-up forms of self-regulation. We begin by contextualizing yoga in historical and contemporary settings, and then detail how specific components of yoga practice may affect cognitive, emotional, behavioral, and autonomic output under stress through an emphasis on interoception and bottom-up input, resulting in physical and psychological health. The model describes yoga practice as a comprehensive skillset of synergistic process tools that facilitate bidirectional feedback and integration between high- and low-level brain networks, and afferent and re-afferent input from interoceptive processes (somatosensory, viscerosensory, chemosensory). From a predictive coding perspective we propose a shift to perceptual inference for stress modulation and optimal self-regulation. We describe how the processes that sub-serve self-regulation become more automatized and efficient over time and practice, requiring less effort to initiate when necessary and terminate more rapidly when no longer needed. To support our proposed model, we present the available evidence for yoga affecting self-regulatory pathways, integrating existing constructs from behavior theory and cognitive neuroscience with emerging yoga and meditation research. This paper is intended to guide future basic and clinical research, specifically targeting areas of development in the treatment of stress-mediated psychological disorders.

Keywords: yoga, self-regulation, stress, executive control, viscerosomatic, top-down, bottom-up

INTRODUCTION

Research suggesting the beneficial effects of yoga interventions on myriad aspects of psychological health has proliferated in recent years: the extant literature suggests that yoga can improve symptoms of depression, anxiety, stress, post-traumatic stress disorder, and other psychological problems (for reviews, see Kuntsevich et al., 2010; Field, 2011; Balasubramaniam et al., 2012; Li and Goldsmith, 2012) as well as promote well-being, including life satisfaction and happiness (Woodyard, 2011). Many different explanations or pathways for these salutary effects have been proposed, but as yet there is no overarching framework in which to understand them. One useful framework for doing so is that of self-regulation.

Theories of self-regulation are assuming an increasingly central role within various sub-disciplines of cognitive science, psychology, and medicine (see Eisenberg, 2000; Watts, 2000; Gross and Thompson, 2007; McCullough and Willoughby, 2009; Hagger, 2010; Hofmann et al., 2012). Generally speaking, *self-regulation* refers to efforts of monitoring, willpower, and motivation to manage or alter one's incipient responses and impulses so as to pursue or maintain explicit goals or standards (Luszczynska et al., 2004; Baumeister et al., 2007; Zell and Baumeister, 2013). A focus of contemporary psychotherapy is the development of self-regulation tools to reduce psychological distress and improve well-being. For example, many current cognitive-behavioral treatments focus on using top-down cognitive means of self-regulation, such as cognitive reappraisal, reframing, and goal-setting (e.g., Berking et al., 2008). More recent "third-wave" behavioral and cognitive therapies, such as acceptance and commitment therapy (ACT; Hayes and Wilson, 1994), dialectical behavior therapy (DBT; Hayes et al., 1999), and mindfulness-based cognitive therapy (MBCT; Segal et al., 2002) also target self-regulation, through the development of mindfulness-related skills (Baer, 2005). There have been suggestions in the recent literature that such mindfulness-based approaches may function through both top-down and bottom-up mechanisms of self-regulation (Chambers et al., 2009; Taylor et al., 2010; van den Hurk et al., 2010; Hölzel et al., 2011b; Vago and Silbersweig, 2012; Chiesa et al., 2013; Westbrook et al., 2013). Top-down strategies are thought to occur in more novice meditators, where there is an emphasis on attentional control and thus, top-down executive mechanisms. As the meditation practice deepens, emphasis on interoception increases, evaluation processes decrease across contexts, and bottom-up strategies may be more strongly present. Bottom-up regulation strategies have been described as modulation of emotion-generative brain regions (i.e., limbic) without recruitment of "higher" brain regions (i.e., frontal) that are responsible for cognitive forms of regulation (e.g., reappraisal, suppression; Taylor et al., 2010; van den Hurk et al., 2010; Gard et al., 2012b; Vago and Silbersweig, 2012; Chiesa et al., 2013). More specifically, bottom-up processes involve the influence of peripheral sensory, visceral, cardiovascular, immune, and autonomic input upon central neural processing and mental activities via ascending pathways (Taylor et al., 2010; McRae et al., 2012). Yoga, as we describe the practice here, is a complex, adaptive and widely applicable method of physical and mental training with multiple tools for self-development, and, as we propose, for improving self-regulation through both top-down and bottom-up mechanisms.

In our integrative systems network model, we propose that specific aspects of yoga practice affect self-regulation through tonic feed-forward and feed-back loops across multiple systems, which, in turn, promote psychological and physical health and well-being. *Specifically, we describe how yoga may function through top-down and bottom-up mechanisms for the regulation of cognition, emotions, behaviors, and peripheral physiology, as well as for improving efficiency and integration of the processes that subserve self-regulation.* We begin by contextualizing the system of yoga in historical and contemporary settings. Then we detail how specific components of yoga practice may affect cognitive, emotional, and behavioral systems under stress, potentially resulting in improvements in physical and psychological functioning during practice and in the midst of living everyday life. The hypothesized mechanisms are then integrated in a theoretical model for self-regulation through yoga and finally scientific evidence in support of this model is provided. The intention for this paper is to provide a theoretical framework that can guide future basic and clinical research and specifically guide development in the treatment and prevention of stress-mediated psychological disorders.

YOGA PHILOSOPHY: A FOUNDATION FOR SELF-REGULATION[1]

In this section a brief historical and philosophical background of yoga will be provided. Yoga, originating from India, is an ancient contemplative practice dating back over 3,500 years, which aims at one thing – to alleviate suffering and promote optimal physical and mental thriving (Cope, 1999; Feuerstein, 2011). In Western contemporary settings, yoga tends to be synonymous with yoga postures, breathing, and some meditation practices. Historically, however, the practice of yoga was understood to be much broader and more comprehensive, including a wider range of techniques to promote wellbeing and balance among mind–brain–body functions. These included paths oriented to service, devotion, intellectual discernment, and meditation, and each offered practices to mitigate suffering and produce higher levels of consciousness (Feuerstein, 2011).

There are many branches of yoga that have developed historically; however, we focus specifically on *Raja* and *Hatha* yoga because of their prevalence in modern practice and their emphasis on developing self-regulation. *Raja* or classical yoga is a system of meditation, while *Hatha* or post-classical yoga followed *Raja* yoga and elaborated upon postures and breathing techniques largely to prepare for meditation. Accordingly, modern yoga practitioners—who practice for purposes beyond physical fitness—study *Hatha* yoga within the context of *Raja* yoga (Vivekananda, 2001). We also focus on *Raja* yoga because many of its components can be linked to modern physical and mental self-regulation concepts. As will be discussed in more detail in the next section, these components can be linked to self-regulatory processes such as goal-setting (top-down ethics), observation of one's behaviors in relation to these goals (top-down attentional processes and bottom-up sensing during postures, pranayamas, and meditation) and cultivation of the ability to override incipient responses in order to move closer to goals (including ethical motivations; McCullough and Willoughby, 2009; Zell and Baumeister, 2013).

The focus of *Raja* yoga, as outlined by Patanjali (author of the *Yoga Sutras,* a historic text of *Raja* yoga, circa start of the common era), was primarily cognitive. Patanjali described yoga as the stilling of distorted fluctuations or ruminations in the mind, which are the sources of suffering (Vivekananda, 2001; Cope, 2006). The multicomponent process of *Raja* yoga is aimed toward training the mind to be effortlessly quiet, focused, and self-aware. These cognitive goals of *Raja* yoga overlap with some goals of other meditative traditions such as Buddhism (Feuerstein, 2011), from which the modern concept of mindfulness has sprung (Kabat-Zinn, 1994; Bodhi, 2011). Some scholars in the humanities consider Patanjali and Shakyamuni Buddha as contemporaries. According to them, in the process of his self-transformation, the Buddha studied and mastered Upanishadic yoga techniques, and his teachings were influenced by these experiences (Feuerstein, 2008; Gombrich, 2009; Gethin, 2011), but see (Bronkhorst, 2007, 2013). Furthermore, the cross-pollination of yoga and Buddhism is most evident in the overlap of Vajrayana Buddhism and *Hatha* yoga (Feuerstein, 2011). A modern example of this overlap is the mindfulness-based stress reduction (MBSR) program, which includes some Hatha yoga postures (Kabat-Zinn, 1990). Although much of the mindfulness-based practices emphasize the mental form of training, some elements of yoga asana and pranayama remain in MBSR. Interestingly, one study of participants from nine different MBSR courses found yoga practice time to be more strongly correlated with self-reported improvements in mindfulness, perceived stress, anxiety, and psychological

[1]In the following summary of yogic concepts that may relate to self-regulation, we included key yogic terms italicized in Sanskrit for historical reference.

well-being than formal sitting meditation time during the 8 weeks (Carmody and Baer, 2008).

Patanjali's *Raja* yoga offers eight different groups of practices aimed toward self-regulation. In Patanjali's *Yoga Sutras*, these different groups of practices are called the eight limbs (**Table 1**), and include: moral observances (ethics when interacting with others); self-discipline (ethics geared toward the self); physical postures and exercises; breath regulation; sensory withdrawal (minimizing sensory input); concentration (effortful, focused attention); meditation (effortless, unbroken flow of attention), and self-transcendence (Stone, 2009). Collectively, the eight limbs may be conceptualized as methods to regulate emotions, thoughts, or behaviors and to increase well-being (Cope, 2006). The diversity of limbs allows students to begin yoga by working with practices that are most appealing and accessible, often the physical postures for Western students.

YOGA'S TOOLS FOR SELF-REGULATION: HISTORICAL AND MODERN INTERPRETATIONS

In this section, we describe the components of *Raja* yoga on which we base our proposed model of self-regulation. To this end we linked classical components of yoga to modern, scientific concepts. We have grouped the eight limbs under the following four categories referred to herein as "process tools" (**Table 1**), because a combination of these four categories encompasses most modern

Table 1 | Components of classical yoga (the eight limbs of Patanjali's *Raja* yoga).

ETHICS

Yamas	**Moral observances**
Ahimsa	Non-violence
Satya	Truthfulness
Asteya	Non-stealing (not taking from others)
Brahmacharya	Moderation of senses
Aparigraha	Non-greedy (not keeping from others)

Niyamas	**Self-disciplines**
Saucha	Cleanliness and purification
Santosha	Contentment
Tapas	Literally 'heat' - austerity
Svadhyaya	Self-reflection and study
Isvara Pranidhana	Surrender

POSTURES

Asana	**Postures**
	Standing poses
	Balancing poses
	Forward bends
	Backbends
	Twists
	Inversions
	Restorative poses
Vinyasa	Breath-linked movement of poses

BREATH REGULATION

Pranayama	**Breath regulation**
Nostril breathing	Slow,deep diaphragmatic
	Epiglottal constriction
	Altered rate or depth
	Uninostril
Mouth breathing	Through curled/flat tongue or teeth
Breath with sound	Sighing
	Humming or bee breath
Retentions	Holding breath in or out
	Ratios of in, out & retentions

MEDITATION

Pratyahara	**Sensory withdrawal**
	Relaxation techniques
	Inward-mindedness
	Minimizing sensory input

Dharana	**Concentration**
	Single-pointed, focused attention
	Object-based
	Effortful

Dhyana	**Meditation**
	Unbroken flow of attention
	Object-based or not
	Open monitoring
	Effortless

Samadhi	**Integration**
	Merging of subject & object
	Transcendental consciousness
	Self-realization

Legend of Modern Usage

(solid box)	Typical modern entry points
(dashed box)	Also in traditional practices
(no brackets)	Advanced traditional practices

These components are described by their modern usage, and grouped into four operational categories that are used to conceptualize how yoga may influence self-regulatory processes.

yoga classes (Field, 2011) and most research on yoga emphasizes these particular practices (Li and Goldsmith, 2012): (1) Ethics, based on the two ethical limbs (moral observances (Sanskrit*: yama*) and self-disciplines (Sanskrit*: niyama*)); (2) Postures (Sanskrit: *asana*); (3) Breath regulation (Sanskrit*: pranayama*); and (4) Meditation, including the four meditative limbs (sensory withdrawal (*Sanskrit: pratyahara*), concentration (Sanskrit*: dharana*), meditation (Sanskrit*: dhyana*), and a deep level of concentration or absorption also described as self-transcendence (Sanskrit*: samadhi*)).

ETHICS (YAMA AND NIYAMA)

On the foundation of the yogic path of self-regulation lie ethical and moral precepts, which are specific examples of the standards or guidelines that contribute to self-control suggested by Zell and Baumeister (2013). These ethical precepts are contained in the first and second limb of Patanjali's eightfold *Raja* yoga path, namely *yama* and *niyama,* respectively. *Yama* refers to ethics regarding the outside world, and therefore is particularly important in social contexts. It comprises non-violence (Sanskrit: *ahimsa*), truthfulness non-stealing, moderation of senses, and greedlessness. *Niyama* refers to ethics regarding the inner world. It comprises purification or cleanliness and contentment, austerity (Sanskrit: *tapas*), self-reflection and surrender or devotion to something greater than oneself. As such, the ethics suggested in yoga are devoid of religious connection—they are not based on moral value judgments of right and wrong—but are rather seen as actions that help to quiet an overactive mind, regulate emotions, and enhance prosocial and skillful behaviors (Cope, 2006).

POSTURES (ASANA)

In Patanjali's *Yoga Sutras*, the limb of *asana* is defined as steady and comfortable posture (Cope, 2006). Physically challenging postures are further described to be sustained through the fluctuations of the mind (Faulds, 2005). Postures are one of the most commonly utilized yoga practices in modern interpretations. Historically, postures were used to physically control the body in preparation for controlling the mind in meditation for extended periods of time (Feuerstein, 2011). A common premise behind modern yoga classes is that practicing various postures may help to reduce physical and emotional stress. A typical yoga class will include a series of postures targeting different parts of the body. For example a class might include forward and backward bends, twists, standing poses, and balancing poses (**Table 1**). Modern and historic yoga practice manuals such as *Light on Yoga* (Iyengar, 1995) often suggest a connection between emotional states, physical health, and postures. Although this link has not scientifically been established yet for any particular poses (or set of poses) specifically, there is evidence linking posture, emotion, and mental health (Michalak et al., 2009, 2011, 2014). We attempt to address these hypothesized benefits in the following section.

BREATH REGULATION (PRANAYAMA)

The Sanskrit word *pranayama* is composed of the word *prana*, which translates to breath as a life-sustaining force, and the word *ayama* which translates to freedom or release. *Pranayamas* are a series of specific techniques to control the breath in order to allow the breath and life force to flow freely (Sovik, 1999). Traditionally, two benefits of *pranayama* are described to help the practitioner down-regulate arousal and increase awareness of the interaction between the body and the mind (Sovik, 1999). Similar to *asana* as preparation of the body for meditation, *pranayama* is meant to prepare the mind for meditation. *Pranayamas* differ from normal breathing on a number of dimensions, including the duration of the in breath, the out breath, the holding of the breath, and the ratio of these. All *pranayamas* involve diaphragmatic breathing, mostly deep and slow in quality through the nose (Jerath et al., 2006). Popular pranayama techniques include deep, even, three-part inhales and exhales, alternate nostril breathing, forceful expulsion of breath using the diaphragm and abdominal muscles, and slow diaphragmatic breathing with partial closure of the glottis creating an audible sound of rushing air described "like an ocean." For a more extensive overview of *pranayamas* see Singh et al. (2009).

MEDITATION (PRATYAHARA, DHARANA, DHYANA, SAMADHI)

Postures and breathing practices are traditionally described to support and foster meditation practices (Faulds, 2005). In the yoga tradition, the concentrative meditation techniques described in *Raja* yoga help the practitioner begin to see the conditions that lead to mental and emotional suffering (fluctuations) and the conditions that remedy suffering (i.e., mental stillness). Suffering is further described as a time when the mind is in an afflicted state—either grasping onto an experience, not wanting to let it go, or experiencing aversion, trying to push some object of experience away with force. In both cases, how one relates to one's inner experience will create either more or less suffering. Such suffering can also be described as a mental state that prevents the mind from seeing reality without emotional bias. The ability to see reality clearly without bias, through meditation practices, is a revered tool of self-regulation within yoga (Cope, 2006) and similarly in mindfulness traditions (Vago and Silbersweig, 2012).

The various forms of meditation in the *Raja* yoga tradition are considered key tools in the regulation of the mind (**Table 1**). Specifically, *Raja* yoga includes a set of concentration practices. For example, sensory withdrawal (*Sanskrit*: *pratyahara*) involves techniques to minimize external distractions from sensory information, facilitating a calm mind and allowing attention to turn inward. Many modern yoga classes conclude with supine rest pose (*Sanskrit: savasana*), the body relaxed and eyes closed. *Pratyahara* techniques include guided relaxation (e.g., *yoga nidra*), which serve as an invitation for students to draw their attention to their inner experience.

The next phase of meditation is called *dharana*, coming from the Sanskrit word "dhr" or to hold tight. In *dharana* the practitioner aims to focus the mind on a single object of meditation such as the breath, a point on the body or an external object (e.g., candle flame) and attempts to maintain focus on that object. At this stage of practice, focused attention requires effort as the mind repeatedly wanders. A key goal of *dharana* is to minimize mind wandering (similar to focused attention meditation (see Benson, 2000; Lutz et al., 2008; Hasenkamp et al., 2012), such that when one realizes the mind has turned away from the object of meditation, the mind is continually brought back to the object.

Occasionally the mind ceases wandering, and meditation shifts into what *Raja* yogis consider more advanced meditative practices, *dhyana*. With time and practice, wandering decreases, as does effort to maintain focus, and an unbroken chain of awareness rests on the object of meditation (Telles et al., 2010; Feuerstein, 2011). As this mastery occurs, there is less effort to keep the mind on the object of concentration and a natural concentrative ease begins to happen. The mind begins to become completely absorbed in the object of attention and a sense of union with the object of attention can begin to occur (Cope, 2006). An analogous process is the psychological flow state experienced by advanced musicians and athletes (Csikszentmihalyi, 1997; Khalsa et al., 2009).

This leads to the final meditative limb, *Samadhi*, which represents transcendent states of conscious awareness and absorption associated with a non-dual subject/object distinction (Josipovic, 2010; Travis and Shear, 2010). *Samadhi* has been described as an experience of no conceptualization, where the object is known directly, beyond name and form. This state of meditation offers a deep sense of interconnection and "sameness" with all phenomena (Cope, 2006). While these experiences of *dhyana* and *samadhi* are said to have profound effects on the mind, these advanced practices are not commonly taught in modern styles of yoga.

Rather than being taught as explicit practices, these meditative limbs are often offered as a process of meditative focus throughout practice. For example, Kripalu yoga, a modern style of *Raja* and *Hatha* yoga, emphasizes witness consciousness, or the observation of experience without reaction (Cope, 2006). Witness consciousness can be likened to the state of mindfulness, often described as "paying attention in a particular way: on purpose, in the present moment, and nonjudgmentally" (Kabat-Zinn, 1994, p. 4). In yoga class, students are guided into a pose, invited to deepen their breath, and then to witness (be mindful of) their experience. The specific limbs that fall under the category of "meditation" are all essential factors that are described to co-arise through the prescribed practices and with the other limbs for progression and mastery. Importantly, witness consciousness can be thought of as a critical mental factor that arises with the other factors serving yoga, but also with the quality of monitoring the development and balance of the other limbs.

The modern use of yoga tends to synergize some of the meditative techniques with postures, breathing, and ethics (**Table 1**). As such, yoga is a unique practice because it offers a variety of complementary tools with which the practitioner can increase self-regulation.

A THEORETICAL MODEL OF SELF-REGULATION THROUGH YOGA PRACTICE: HOW CURRENT COGNITIVE NEUROSCIENCE AND PSYCHOLOGICAL THEORY CONTRIBUTES TO REVEALING MECHANISMS OF YOGA

As discussed above, yoga can be broken down into a skillset of four tools for self-regulation: (1) ethical precepts, (2) sustained postures, (3) breath regulation, and (4) meditation techniques. Here we propose a model (**Figure 1**) that describes how this skillset may facilitate self-regulation and results in psychological and physical well-being. In this model, we propose how yoga skills facilitate bidirectional feedback and improve integration and efficiency of high-level (e.g., central executive network, frontal–parietal control network) and low-level brain networks (e.g., autonomic systems, vagal complex, striatopallidal–thalamocortical network) along with viscerosomatic, musculoskeletal, cardiac, respiratory, and sensory information coming from the periphery (see **Table 2** for description of networks). As depicted in **Figure 1**, maladaptive cognitive, emotional, and behavioral output (e.g., negative appraisal, emotional reactivity, rumination), as well as physiological output initiated by lower-level brain systems (e.g., sympathetic-related vaso- and pulmonary constriction, inflammation, muscle pain/tension) that disrupt homeostatic conditions across bodily systems (including cardiovascular, neuroendocrine, and musculoskeletal) are extinguished and replaced with more adaptive output to the challenging demands of stress in the context of practice and in more generalizable settings. Integration between top-down and bottom-up processes is also proposed to improve accuracy of prediction and error correction mechanisms associated with the stress response across domains, resulting in further improving accuracy in detecting and efficiently responding to perceived threats and reducing consequences of prolonged stress exposure. Finally, the model poses that regular practice is partially motivated and enhanced by a particular set of ethical beliefs promoting benefits toward oneself and others, including direct reward resulting from the practice. Thus, increased activation of a higher level moral cognitive network (see **Table 2**) is hypothesized to be associated with improved ethical skills. It is understood that placebo-related mechanisms may also operate to fuel effective top-down control and motivation; however, such mechanisms remain unclear. Nonetheless, motivation provides realistic goals and positive intentions to fuel approach behavior and provides the scaffolding to support the ethical framework built in to the practice.

TOP-DOWN INFLUENCES ON SELF-REGULATION

Here, we propose top-down self-regulatory mechanisms of yoga include control of intentional/motivational drive (e.g., goal-setting and maintenance), working memory, attention, executive monitoring, response inhibition, reappraisal, and meta-awareness (see yellow boxes within high-level brain networks in **Figure 1**). Such control signals include generation and maintenance of attention on the object of practice, which includes a continuous focus on an object of visual attention (e.g., point in space), aspect of the breath, or interoceptive feedback from body sensation or mental activity. Furthermore, cognitive reappraisal of feedback from the body is proposed to facilitate inhibitory tone toward maladaptive cognitions, emotions, or behavior.

Yoga is often called "meditation in motion" (e.g., Khalsa et al., 2009) for its highly focused attention during bodily movements. Attention is often directed to a specific part of one's body (e.g., ball of foot, fingertips) or an external point (Sanskrit: *drishti*); similarly, in pranayama, practice involves focusing on the breath as it moves through the body. The focus of one's gaze on one point facilitates the "withdrawing" of the sense of vision away

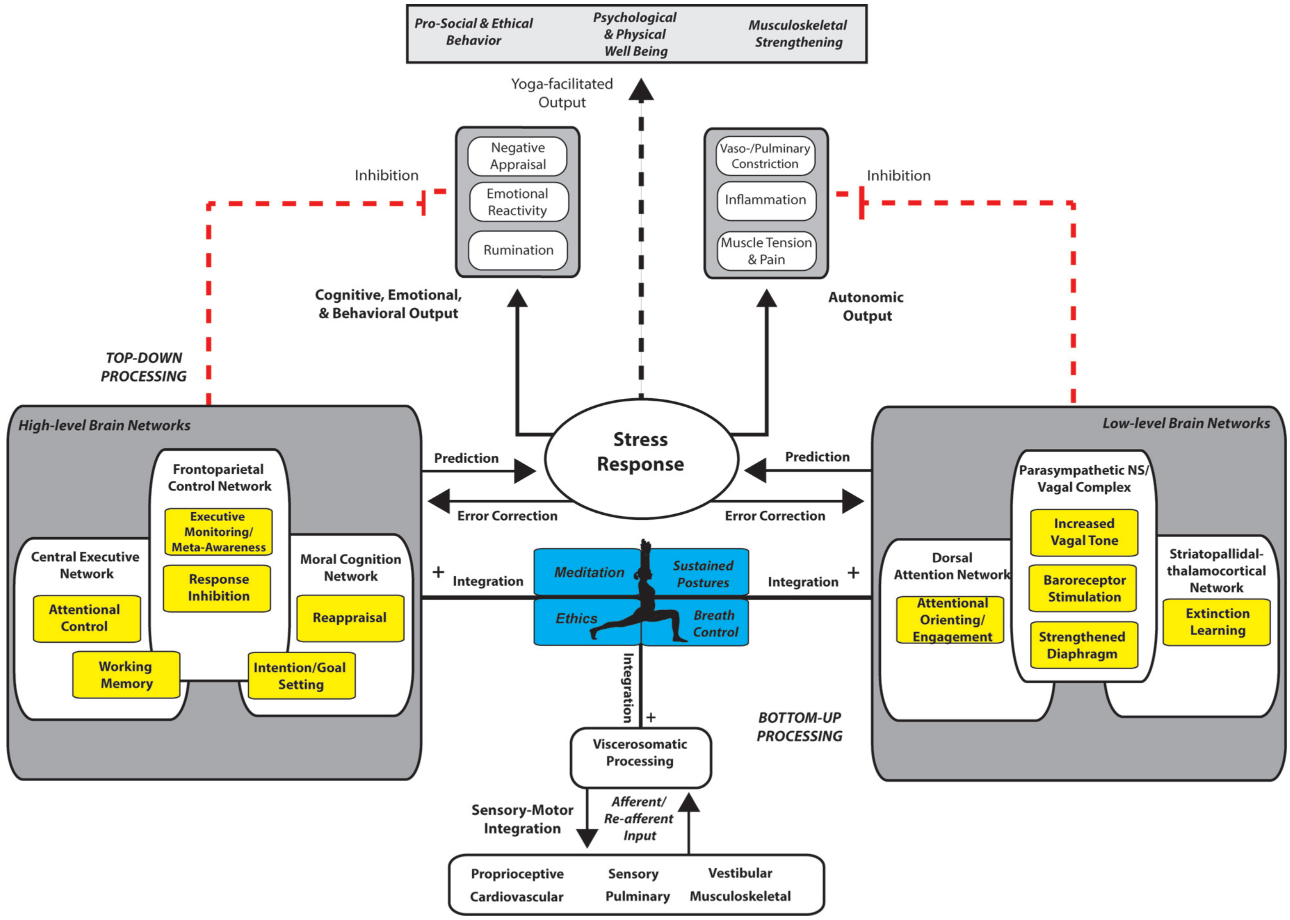

FIGURE 1 | Systems network model of yoga for optimizing self-regulation. The major limbs of yoga are represented in blue boxes as a skillset of four process tools: ethics, meditation, breath regulation, and postures. Application of these skills (limbs of yoga) across cognitive, emotional, behavioral, and autonomic domains in the context of physical and emotional stress is proposed to generalize to similar challenges off the yoga mat and in everyday life. Together, these tools of yoga improve the efficiency, bidirectional feedback, and integration (+ black lines) between high- and low-level brain networks, and afferent and re-afferent input from interoceptive processes (e.g., multi-sensory, proprioceptive, vestibular, cardiovascular, pulmonary, musculoskeletal) in the context of stress. Through an emphasis on interoception and bottom-up input, integration facilitates inhibition (red lines) of maladaptive forms of cognitive, emotional, and behavioral output as well as autonomic output associated with stress. Efficiency improves the communication and flexibility between brain and bodily systems to inform behavioral output. Yoga's four tools are described to involve particular regulatory processes associated with each set of brain networks (indicated in yellow boxes). With mastery of practice, regulatory processes become more automatized, requiring less effort to initiate when necessary and terminate more rapidly when no longer needed. A central executive network supports top-down mechanisms of attentional control and working memory allowing monitoring for proper goal-directed behavior followed by self-correction if needed. A FPCN supports executive monitoring, meta-awareness, reappraisal, and response inhibition mechanisms. A moral cognition network supports motivation and intention setting associated with self-care and prosocial behavior. The dorsal attention network helps to support attentional orienting, and engagement. Hypothlamic–pituitary–adrenal (HPA) axis communication with brainstem vagal efferents support parasympathetic control and homeostasis across systems. A striatopallidal–thalamocortical network is responsible for facilitating extinction learning and reconsolidation of maladaptive habits into behavior that is aligned with intentions and outcomes into adaptive habits. Dotted lines represent new, adaptive pathways for responding to stress. A focus toward bottom-up processes facilitates a shift toward perceptual inference rather than active inference, and improves prediction and error correction processes, thus supporting optimal self-regulation.

from distraction, while the focus of one's attention inward and on body sensation contributes to the "withdrawing" of the other senses from distractions. Distraction is the loss of selective attention and focus on sensory experience outside of a single point or prescribed focal points. Rapid disengagement from distraction and re-engagement on the object of focus is also believed to be a top-down strategy (Koster et al., 2011), although early attentional filtering may involve more bottom-up sensory processing (Kerr et al., 2013). Attentional stability in the context of stressors induced through yoga practice is thought to reduce negative forms of appraisal and ruminative thought processes by maintaining awareness and attentional engagement with sensation in the body (McCall, 2007). This form of intentional concentration on particular sensations and not others is critical to cognitive flexibility of attention and inhibitory control – the ability to sustain attention on meaningful information and disregard irrelevant information from the external and internal environment. Sensory withdrawal, one of the originally described "limbs" of

Table 2 | High-level and low-level brain networks.

Central executive network		
Dorsal parietal cortex	Superior parietal lobe (sPL)	Dorsal frontal cortex
Frontoparietal control network		
Frontopolar cortex	Dorsolateral prefrontal cortex (dlPFC)	Dorsomedial prefrontal cortex (dmPFC)
Anterior cingulate cortex (ACC)	Anterior inferior parietal lobe (aIPL)	Anterior insular cortex (AIC)
Temporo-parietal junction (TPJ)	Ventrolateral prefrontal cortex (vlPFC)	
Moral cognition network		
Ventromedial prefrontal cortex (vmPFC)	dmPFC	Posterior cingulate cortex (PCC)
Precuneus	Middle temporal gyrus (MTG)	TPJ
Dorsal attention network		
Frontal eye fields (FEF)	Ventral premotor cortex (vPMC)	sPL
Dorsal parietal cortex	Supplementary motor area (SMA)	Ventromedial posterior nucleus–thalamus (VMpo)
Pulvinar	Superior colliculus (sc)	
Striatopallidal–thalamocortical network		
Orbitofrontal cortex (OFC)	ACC	Dorsal striatum
Thalamus	Pallidum	VTA/SN

Patanjali's yoga, is therefore conceptualized here as contributing to cognitive factors of selective attention and response inhibition, further reducing autonomic reactivity and habitual tendencies to respond to external and internal experience in maladaptive ways.

A central executive network has been found to be most consistently active for the described forms of explicit attention and cognitive regulation, including the dorsal parietal cortex along the intraparietal sulcus, extending dorsomedially into the superior parietal lobe, and anteriorly toward the post-central sulcus, and the dorsal frontal cortex (Corbetta and Shulman, 2002). In addition to the central executive network, a fronto-parietal control network (FPCN) is also proposed to help facilitate executive monitoring (of internal and external information) and meta-awareness, guidance of decision making, salience detection, and integration of information from the external and internal environment (Seeley et al., 2007; Vincent et al., 2008). This network includes the frontopolar cortex (FPC), dorsolateral and ventrolateral prefrontal (dlPFC, vlPFC), dorsomedial superior frontal/anterior cingulate cortex (ACC), anterior inferior parietal lobe (aIPL), temporoparietal junction (TPJ), and anterior insular cortex (AIC; Vincent et al., 2008; Spreng et al., 2013). One central aspect of yoga practice thought to facilitate the engagement of this network is meditation and its associated skills for fostering stable attention through active inhibition of specific brain regions responsible for processing internally generated contents of our attention (e.g., default mode network DMN) and facilitation of executive monitoring and present-centered sensory processing.

Meta-awareness or self-awareness (Zell and Baumeister, 2013) may be another mechanism through which yoga improves self-regulation. Increased meta-awareness would allow individuals to clearly compare their current status *vis à vis* their goals and to make any necessary behavioral adjustments. Meta-awareness is often cited along with psychological distancing (Ayduk and Kross, 2010) or decentering (Fresco et al., 2007), a process that allows the individual to uncouple the sensory experience from the "narrative" self and gain perspective of one's world-view and habits, and increases the likelihood of behavioral change (Critchley et al., 2004; Vago, 2014). Furthermore, the de-centered perspective allows one to experience thoughts and emotions in terms of their subjectivity (rather than an assumed validity) and their transient nature (rather than their assumed permanence; Fresco et al., 2007). Such awareness is thought to override short-term impulses in favor of long-term considerations, effectively improving one's ability to reflect upon the past and use that information accurately to anticipate the future, and to more accurately assess the present (Baumeister et al., 2011). This form of awareness has also been shown to facilitate prediction of error detection and correction, and as a result, more rapidly improve behavioral correction processes when regulating emotional responses to stress (Compton et al., 2008).

With support from the neuroscientific literature (Critchley et al., 2004; Craig, 2009; Taylor et al., 2010), our model suggests that meta-awareness of interoceptive experience facilitates integration across primary sensory, visceral, homeostatic, environmental, hedonic, and social levels via feedforward and feedback between higher-level and lower-level brain networks. For example, there is good evidence that salience-specific nodes of the FPCN (ACC, and insula), interact to develop modulatory influence over viscerosomatic afferent activity arising through the spinal–thalamo-cortical pathway (Craig, 2004). The insula specifically processes interoceptive input in a hierarchical fashion – in a posterior to anterior direction (Craig, 2009), with more basic sensory and homeostatic information in the posterior and more salient, hedonic, and social information in the anterior. Such interaction and integration are proposed to result from the strengthening of the executive monitoring system similarly to mindfulness-based meditative practices (Vago and Silbersweig, 2012; Desbordes et al., 2014). Mindfulness practice encourages practitioners to take a meta-cognitive view of their experience, to notice the experience without judging it or modifying it and is thus, a form of self-regulation. Yoga offers a way to practice mindful awareness in this way, described above as "witness consciousness."

Self-regulation of emotion refers to the management of the felt experience of emotions, both positive and negative in valence, its behavioral expression, and associated autonomic output, through cognitive reappraisal and through a process of non-appraisal that involves awareness alone, a form of attentional control that does not involve evaluation or judgment (Davidson and Irwin, 1999; Critchley et al., 2003; Vago and Silbersweig, 2012). We theorize that emotional stability and rapid recovery from perturbation arises from either strategy. Similarly to the difference between beginning and experienced mindfulness meditators, non-appraisal is believed to be more advanced and more likely in experienced yoga practitioners than in novices (Taylor et al., 2011). The rapid recovery from emotional perturbation has been referred to as equanimity in the Buddhist and secular mindfulness literature. Equanimity, defined as an even-minded mental state or dispositional tendency toward all experience, regardless of affective valence or source (Desbordes et al., 2014), is proposed to be a skill that is manifested through efficient feed-forward and feedback between somatic, autonomic, viscerosensory, and high-level brain network activity that continually manages stressors that arise on and off the yoga mat.

Positive reappraisal is yet another important cognitive and emotion regulation skill that can be enhanced by yoga. Positive reappraisal has been proposed to mediate the stress-reductive effect of mindfulness through an upward spiral process (Garland et al., 2011). For example, much of yoga practice involves learning to reframe experiences (e.g., from discomfort to sensation), teaching a more objective, observational, and non-judgmental stance to one's experience (Garland et al., 2011). Other reappraisal resources can be acquired through yoga practice. For example, in the course of yoga classes, teachers often instruct students about deeper aspects of yoga philosophy, such as compassion and impermanence, which are useful in appraising or reappraising situations as less stressful (Nyklíček, 2011). Kripalu yoga promotes a technique of "riding the wave" (Faulds, 2005), which involves reappraisal and behavioral change that allows toleration of discomfort – reframing the discomfort of muscle fatigue to a temporary sensation that will pass. Recent theories on self-regulation postulate that explicit reappraisal strategies can reduce the negative impact of prolonged and repeated high stress-related neuroendocrine activity (Koole et al., 2011; Geisler et al., 2013). Reductions in perceived stress lead to conserved cognitive resources and less prolonged (or perseverative) negative emotion (e.g., anger, frustration) along with peripheral effects (e.g., increased vasodilation) that improve outcomes (Jamieson et al., 2012; Keller et al., 2012). The development of equanimity and meta-awareness may also improve self-other interactions and therefore contribute to ethically informed pro-social behavior.

Yoga is also proposed to enhance behavioral forms of self-regulation through goal-directed influence over one's behavior "on and off the yoga mat." This is a topic particularly relevant to health psychology (Mann et al., 2013), such that health-promoting behaviors are more likely once a practitioner has committed to the system and practice of yoga and has an attitude supporting "readiness" or "willingness to change." For example, readiness to change has been found to be a significant factor driving clinical change in addiction settings (DiClemente et al., 2004). Regulation is proposed to occur via continual adjustment and guidance of one's behavior (e.g., maintain a particular body position even if one's muscles ache and the impulse is to relax) in pursuit of ethically motivated actions associated with self-care, health-promoting behavior, and pro-social interactions (e.g., increased empathic behavior). Behavioral strategies may also limit exposure to stressful situations. For example, the individual may avoid potentially stressful situations and employ proactive coping strategies to prevent them (Aspinwall and Taylor, 1997) or engage in socially adaptive behaviors (e.g., seek social support; Geisler et al., 2013), both of which are behavioral forms of self-regulation. In addition, yoga practitioners may move toward more healthy lifestyles (e.g., involving less substance abuse, decreasing their risk for substance-related accidents, healthy eating habits; Khalsa et al., 2008; Carei et al., 2010). Thus, behavioral regulation also encompasses a range of inhibitory response behaviors, such as overriding impulses, habits, or cravings, employing approach-focused coping (van Gaal et al., 2011), and facilitating ethical behavior. The effects of yoga on cravings and aversions remain unclear and pose an interesting question for future research.

Yoga can be considered a "wisdom-based" contemplative practice (Cope, 2006), providing an ethical framework that is based on discernment of right and wrong action. Particular ethical precepts of yoga practice are rarely taught formally in Western yoga classes, but they may be conveyed in more indirect ways, such as through modeling, suggestions for goal-setting, or technique instructions that may include attitude and awareness of self and other. In Kripalu yoga, for example, gentleness and respecting one's own boundaries are important aspects of the instructions. These instructions may convey the ethics of non-violence (*ahimsa*) and contentment (*santosha*). Conceptually these two ethics may be related to (self)-compassion, which has been shown to be cultivated through yoga and which mediates the positive effects of yoga on well-being and perceived stress (Gard et al., 2012a). Shapiro et al. (2012) argue that while ethics form the foundation for the cultivation of other mental qualities as described in yoga as well as in Buddhist traditions, the cultivation of states of discernment and meta-awareness even in the absence of explicit training in ethics would affect moral reasoning and decision making in an implicit way. Such changes have been suggested to be mediated by mechanisms of sensory–perceptual clarity, enhanced compassion, values clarifications, and increased emotional awareness and regulation (Eisenberg, 2000). Indeed, improved moral reasoning and decision making along with improvements in witness consciousness, which includes states of discernment like mindfulness, have been reported two months after a MBSR intervention, suggesting that contemplative interventions that incorporate mindfulness and yoga can result in development of these ethical aspects without explicit teaching of them (Shapiro et al., 2012). Similarly, Thiel et al. (2012) propose that emotion regulation, self-reflection, and information integration are three of the four strategies affecting ethical decision making. Interestingly, all of these three constructs are thought to be affected by MBSR and trait mindfulness (Hölzel et al., 2011b), a trait found to be cultivated through yoga (Gard et al., 2012a).

Numerous neuroimaging studies have investigated the neural underpinnings of moral decision making. A recent meta-analysis revealed that moral cognition involves a brain network including ventromedial prefrontal cortex (vmPFC), dorsomedial PFC, posterior cingulate cortex (PCC), precuneus, middle temporal gyrus, and TPJ (Bzdok et al., 2012). This network has several nodes in common with networks supporting theory of mind and empathy, suggesting that moral cognition and prosocial behavior involve integration of both socio-cognitive and socio-affective networks (Bzdok et al., 2012). Interestingly, MBSR has been shown to improve moral cognition (Shapiro et al., 2012) and empathy (Shapiro et al., 2011) and modulate structures associated with perspective taking (Lazar et al., 2005; Hölzel et al., 2011a,b). Likewise, we propose yoga practice engages this network to influence and regulate behavior and prosocial skills.

BOTTOM-UP INFLUENCES ON SELF-REGULATION

We emphasize that as opposed to classical psychotherapeutic approaches for self-regulation that rely only on cognitive strategies, mind–body approaches including yoga involve both top-down and bottom-up mechanisms (see Taylor et al., 2010; Chiesa et al., 2013). Successful self-regulation through bottom-up mechanisms is proposed to facilitate improved function in a network of low-level brain structures (associated regulatory processes indicated by yellow boxes in **Figure 1**) responsible for peripheral physiological activity and reorganization, including stimulation of somatic, visceral, and sensory receptors, extinction processes, and integration with homeostatic physiology. Specifically, we propose yoga practice involves coupling between the body and environment that facilitates embodied viscerosomatic integration and action (see bottom of **Figure 1**). Building upon past theories of somatic processing which emphasize the representation of emotional states in subcortical maps as it interacts with the environment (Damasio, 2010), here we similarly emphasize embodied, situated forms of processing. Viscerosomatic information from the body, including primary sensory and homeostatic information, is proposed here to be continually and reciprocally integrated with motor output and ongoing cognition during sustained body postures, diaphragmatic breath control, attentional control, and dynamic patterns of representative neural activity. The shift in attentional orientation toward the body and significant ongoing reciprocal communication between sensory-motor afferent and re-afferent input supports a model for integration and embodied cognition and behavior (Wilson, 2002; Taylor et al., 2010; Schmalzl et al., 2014).

Embodiment implicitly refers to action coupled with and not separate from the bodily experience. Merleau-Ponty (1996) refers to this experience as, "I am not in front of my body, I am in my body, or rather I am my body." Yoga may offer additional tools of embodiment (e.g., explicitly inducing gross levels of physical sensations) for some populations that sitting meditation alone cannot provide. For example, a few studies have suggested how mindful yoga may be more suited for those with chronic illness or for patients with psychopathology and a history of trauma (van der Kolk et al., 2014). Yoga may support changes in chronic illness schema by challenging beliefs about the limits of one's physical body. As students practice poses and bring awareness to sensation in the body in ways they initially may have felt they could not, they may come to see that while some aspects of their bodies are limited, other parts of the body are still healthy (Hamilton et al., 2006). van der Kolk (2006) described how movement and touch-based practices that focus on the body [embodiment] have demonstrated some level of effective self-regulation, including Feldenkrais, Rolfing, the F. M. Alexander technique, somatic experiencing, among others. van der Kolk (2006) further suggests it is the trauma patients who specifically have learned helplessness and immobility associated with their emotional trauma. Frewen and Lanius (2006) describe how individuals with PTSD are often unable to up regulate their level of arousal during periods of anhedonia or "emotional numbness," which further prevents effective regulation in the context of affective arousal or distress. Thus, body movement during yoga practice and activation of motor and inhibitory control circuits like the striatopallidal–thalamocortical loops in the context of physical arousal may be a more effective way of triggering exposure, extinction, and adaptive reconsolidation of emotions. With embodiment, we propose sensory and perceptual faculties are sharpened – a sense of clarity or greater phenomenal intensity in which sensation is experienced emerges.

Early attentional filtering, a form of primary sensory processing of the environment, may also be affected by yoga practice. For example, a dorsal attention network of brain structures [i.e., frontal eye fields (FEF), ventral premotor cortex (vPMC), superior parietal lobe (sPL), intraparietal sulcus (IPS)] selects information from the sensory world (with direction from top-down influences) and is most associated with covert and overt shifts of spatial attention, eye movements, and hand–eye coordination directed from brainstem nuclei and pre-motor areas (Corbetta and Shulman, 2002; Vincent et al., 2008). Low-level brain networks for this process are typically described to function under conscious awareness, contributing to affective biases of perception (Todd et al., 2012), but also to neuro-visceral integration as described by Thayer and Lane (2000). For example, the "experiential enactive self" network (e.g., supplementary motor area (SMA), ventromedial posterior nucleus of the thalamus (VMpo), pulvinar, posterior insula, and superior colliculus (SC; Vago and Silbersweig, 2012) has been described to contribute to perceptual biases, and to be modulated by mindfulness practice. The posterior insula, a primary node in this network, has been implicated in processing the most basic primary interoceptive information along with homeostatic sensory-motor information (Craig, 2009). It remains unclear how these networks specifically interact as a result of yoga training, but we hypothesize that they are reconditioned to facilitate engagement with body sensations, reduce bias and be more functionally integrated with viscerosomatic input, executive control, and adaptive motor output.

In the context of yoga-induced physical stress and associated emotional reactivity, there is a coordinated set of homeostatic responses involving the interaction among the nervous, endocrine, and immune systems (McEwen, 1998). Overactive or inefficiently managed homeostatic responses can lead to cumulative wear and tear on the body and brain (Sterling and Eyer, 1988; McEwen, 2004). Pathophysiological processes with unfavorable psychopathological outcomes may occur given the following prolonged conditions: (1) if the release of neuroendocrine mediators are not effectively terminated (in the presence or absence of a stress-related physiological challenge), (2) if there is failure to habituate to repeated stress-related challenges, or (3) if there is a failure to mount an adequate response to the stressor (McEwen, 2004). Within this framework, we propose that yoga affects self-regulation through parasympathetic control, in part by physiologically reducing prolonged emotional reactivity and associated autonomic responses, both in terms of acute forms (e.g., during/immediately following a yoga practice) and by shifting a physiological set point for baseline reactivity over repeated, long-term yoga practice. In other words, it may take more physical stress or more intense emotional reactivity to induce a typical "stress response" in addition to promoting parasympathetic tone more rapidly in response to stress. The current model predicts physiological mediators such as the catecholamines (e.g., epinephrine, norepinephrine) from the adrenal medulla, glucocorticoids (e.g., cortisol) from the adrenal cortex, pituitary hormones (e.g., ACTH, prolactin, growth hormones), and inflammatory cytokines (e.g., IL-1, IL-6, TNF-α) from cells of the immune system are modulated directly in various bodily tissues and organs to facilitate rapid homeostasis across all bodily systems effectively managing the bodily responses to the stress of challenging postures and distraction. Furthermore, there is some evidence that meditative components of yoga can increase levels of brain-derived neurotrophic factors (BDNF; Balasubramaniam et al., 2012), a growth factor thought to help support the survival of existing neurons and counteract degenerative effects of inflammation by encouraging the growth and differentiation of new neurons (Huang and Reichardt, 2001). Properly managed stress through the challenges of focusing attention with stillness, balance, and breath control across repeated yoga practice has the potential to promote neurogenesis, dendritic arborization, and increased synaptic connectivity, and can be reinforcing by enhancing neural activity in the "pleasure pathways" of the nervous system (i.e., basal forebrain; Chrousos and Gold, 1992b; Logan and Barksdale, 2008). This change in homeostatic responsivity is a form of skillful optimization of autonomic control to keep arousal at lower levels, helping the practitioner stay relaxed with less effort, and facilitate recovery of bodily systems under stress. Such "calming" effects by contemplative practices have been previously described as the "relaxation response" (Benson, 2000; Dusek and Benson, 2009) and refer to what is described in the extant yoga literature as "steadying the mind." Similarly, it has been suggested that yoga promotes continual neurovisceral feedback and a mechanism of increased inhibition of sympathetic responses post-arousal via branches of the 10th cranial nerve, the vagus nerve, and specific parasympathetic nuclei in the medulla (Streeter et al., 2012). In contrast the to the "relaxation response," the "stress response" refers to both the sympathetic output and cognitive, emotional, and behavioral output that are associated with detection of threat (Benson, 2000).

Parasympathetic responsivity, a form of autonomic nervous system regulation, is described to manifest in cardiac variability or vagal tone (Porges, 1995; Thayer and Lane, 2000). Cardiac vagal tone, measured by respiratory sinus arrhythmia (RSA) and heart rate variability (HRV), indexes the efficiency of central–peripheral feedback mechanisms (Thayer and Lane, 2000). Specifically, RSA is a cardiorespiratory phenomenon that indexes the influence of respiratory frequency and depth of ventilation (i.e., tidal volume) on vagal control of heart rate (HR); whereas, HRV refers to the peak-to-peak variability between successive beats (Grossman and Taylor, 2007). Yoga practice may facilitate high vagal tone (Streeter et al., 2012), which is associated with greater behavioral flexibility in a changing environment and can manifest in decreases in low-frequency HRV, increases in high-frequency HRV, and increased RSA. Vagal tone refers to the activity of the vagus nerve, and its ability to convey afferent (sensory) information about the state of the body's organs to the central nervous system. Porges' (1995) polyvagal theory specifies two functionally distinct branches of the vagus nerve that control the parasympathetic response in opposition to the sympathetic-adrenal system that mobilizes energy in times of stress. One branch, the ventral vagal complex (VVC), originates from the medullary nucleus ambiguous (NA) and provides efferents to supradiaphragmatic target organs (e.g., soft palate, pharynx, larynx, esophagus, bronchi, and heart). The NA also receives input from the trigeminal and facial nerves (Porges, 1995), suggesting influence of facial muscles in controlling cardiovascular, pulmonary, and parasympathetic output. The other branch originates from the medullary dorsal motor nucleus (DMX) and innervates subdiaphragmatic organs (e.g., stomach, intestines; Porges, 1995). Parasympathetic outflow is mediated largely by descending outputs from these nuclei and are under the direct influence of limbic regions associated with emotion-generation and conditioning of behavioral responses to emotional stimuli (Ulrich-Lai and Herman, 2009). One way that breath regulation may modulate parasympathetic output is through VVC efferents that regulate autonomic output, or indirectly through limbic inhibitory projections (Ulrich-Lai and Herman, 2009).

In yoga practice, breath regulation is a key tool for impacting physical and mental states, and vice versa (Faulds, 2005; Telles and Singh, 2013). In this context, diaphragmatic breath control is consciously mediated, but non-consciously influencing parasympathetic activation. The most common form of breath regulation during yoga practice is described as slow, deep, diaphragmatic, and paced along with each movement of the postures (Faulds, 2005); there are however, many other very specific practices that are described. A number of authors have proposed mechanisms for the self-regulatory properties of *pranayama* that support our model. In the late 1970s, *pranayama* was proposed to result in "a steadying of the mind" through the Hering–Berueter reflex (Pratap et al., 1978). Pauses after deep inhalation would result in excitation of baroreceptors (stretch receptors) in the lungs, providing feedback to vagal nuclei and facilitating increased vagal tone (Porges, 1995; described as a low-level brain mechanism in **Figure 1**). Action potentials would then travel along the vagus nerve to the lower pons, signaling inspiration. Increased stimulation of baroreceptors "may functionally alter some areas of the ascending reticular activating system, thereby suppressing sensory input to the cortex, bringing about a steadying of the mind" (Pratap et al., 1978). Other research groups supported this hypothesis and found that controlled breathing decreased chemoreflex response (i.e., a decrease in signaling of pH changes due to metabolic demand) and increased baroreflex sensitivity, both of which are vagus mediated (Spicuzza et al., 2000; Bernardi et al., 2001). An alternative explanation may be that change in respiratory rate results in changes in systolic blood pressure, which modulates the baroreflex (Bernardi et al., 2001). As described earlier, *ujjayi* breathing is a common technique used in combination with *asana* that is thought to strengthen the diaphragm, facilitating pulmonary gas exchange (O_2/CO_2) and circulation in the process (McCall, 2007). Postures that involve particular biomechanical changes in body position (e.g., "heart-opening poses") could theoretically alter pulmonary ventilation, gas exchange, and cardiovascular function (Behrakis et al., 1983; Galanis et al., 2013; Karbing et al., 2013). It has further been suggested that mechanical forces from the body pushing against itself in particular postures may stimulate the hypothalamic–pituitary–adrenal (HPA) axis similar to massage (Rapaport et al., 2012). However, a recent study with yoga naive participants revealed that slow breathing with equal inspiration and expiration is as good in increasing blood oxygen saturation and baro reflex sensitivity as *ujjayi* on the exhalation (Mason et al., 2013). *Ujjayi* on both the inhalation and exhalation did not increase the baro reflex response at all when compared to normal breathing (Mason et al., 2013). This finding seems to be in conflict with a neurophysiological model of *ujjayi* breathing that hypothesized that stimulation of somatosensory vagal afferents and arterial baroreceptor result from the constricted breathing (Brown and Gerbarg, 2005b). Furthermore, holding the breath after inhalation or exhalation is proposed to enhance parasympathetic activity through the vagal afferents that project to the parabrachial nucleus, thalamic nuclei, cerebral cortex, and mesolimbic areas (Brown and Gerbarg, 2005b). Mason et al. (2013) speculate that their finding that *ujjayi* does not increase baro reflex sensitivity more than slow breathing, despite the prediction of the model of Brown and Gerbarg (2005b), might be due to increased effort in this pranayama. Breath regulation may also activate the hippocampus, hypothalamus, amygdala, and stria terminalis, which may subsequently improve autonomic function through coordinated conditioning of inhibitory feedback mechanisms associated with neuroendocrine release, emotional processing, and social bonding (Brown and Gerbarg, 2005b; Jerath et al., 2006; Telles and Singh, 2013). Other more challenging *pranayama* techniques such as the rapid exhaling in *kapalabhati* followed by breath retention or alternating nostril breathing are thought to similarly contribute to neurophysiological changes underlying self-regulation (as reviewed in Telles et al., 2011). A pilot study of HRV dynamics showed intermittent, very high amplitude oscillations in heart rate and high complexity in fluctuations of overall time series during slow breathing despite subjective experience of relaxation, over the course of meditative breathing and chanting exercises by advanced Kundalini yoga practitioners (Peng et al., 1999). These findings may tentatively support the notion that yoga practices including breathing train the ANS to be more dynamically adaptive to stressors (rather than statically quiescent), similar to the neurovisceral integration model of allostasis (Thayer and Sternberg, 2006).

INTEGRATION OF TOP-DOWN AND BOTTOM-UP MECHANISMS

A result of yoga practice is improved integration among top-down and bottom-up mechanisms for self-regulation. Extinction learning is proposed to facilitate integration using bidirectional feedback between executive, viscerosomatic, and homeostatic processes. Our working model proposes the tools of yoga utilize associative mechanisms of extinction learning to re-condition the interactions across bodily systems during physical and/or emotional stress experienced on and off the yoga mat and re-orient cognitive, emotional, behavioral, and physiological output toward adaptive trajectories (indicated by dotted lines in **Figure 1**). Although there is likely to be influence by cognitive processes in an explicit way (see Ochsner and Gross, 2005), implicit sensory processes are conditioned to inhibit natural tendencies for physiological and emotional reactivity and more conscious resources are conserved for urgent, demanding, and exceptional matters (Quirk and Mueller, 2008). Interactions between vmPFC, vlPFC, and limbic areas (i.e., amygdala, hippocampus) have been shown to play both evaluative and non-conscious roles for extinction and behavioral inhibition and act as a hub for coordinating organism-wide visceromotor behavior (Ridderinkhof et al., 2004; Quirk and Mueller, 2008; Roy et al., 2012), thus playing supporting roles in facilitating new associations between body, mind, and behavior. Extinction learning in yoga practice involves integration between embodied movement, viscerosomatic, and homeostatic feedback, and parasympathetic control. We postulate that the extinction mechanism involves interactions among striatopallidal–thalamocortical circuitry, including cortical regions (i.e., dlPFC, ACC, orbitofrontal cortex), basal ganglia (striatum, pallidum), thalamus (mediodorsal nucleus), cerebellum, cortical sensory-motor nuclei (primary sensory, PMA, SMA), and fronto-temporal-parietal networks (Schacter, 1992; Quirk and Beer, 2006; Quirk and Mueller, 2008). These interactions are proposed to facilitate new, adaptive associations responsible for dictating adaptive and stable output.

Increases in tonic activity in striatopallidal–thalamocortical circuitry (including dopamine-containing nuclei) has been specified in implicit learning and automatized cognition (Liljeholm and O'Doherty, 2012) in parallel with top-down cognitive control of action and expectation. It is believed that feedback in iterative "loops" among cortico-subcortical circuits can act to "train" the cortex to produce more adaptive automatized and habitual motor output in the presence of a particular pattern of sensory information and conserve cognitive resources for ongoing task demands (Graybiel, 2008). As suggested earlier by van der Kolk (2006), our model also predicts that such circuitry is likely to become more active in experienced practitioners as the practice becomes more automatized and implicit. Morphometric and functional changes have been seen in this circuitry with fMRI studies of advanced meditators (Lazar et al., 2000; Holzel et al., 2008; Vago et al., 2013; Fox et al., 2014; Luders, 2014). Because of the proposed increases in integration across systems, implicit circuitry does not necessarily imply "unawareness," but rather an ability to flexibly switch between more automatic processing of information and goal-directed manipulation of relevant information (Graybiel, 2008; Vago et al., 2013).

As a result, during the challenging aspects of yoga practice, appraisal processes become more efficient and implicit, resulting in stable attention and affect that may compete with old, previously conditioned stress reactivity, distraction, and affect dysregulation (Quirk and Mueller, 2008; Hartley and Phelps, 2010). This competition between old maladaptive habits and newer, more adaptive ones can be understood as an inhibition of the former by the latter, potentially facilitating adaptation of afferent–efferent and re-afferent processes (see Christoff et al., 2011). Through continued practice, inhibitory control mechanisms become integrated with autonomic, attentional, and affective systems, creating a functional and structural network for self-regulation (Thayer and Lane, 2000). The strengthening of habitual inhibitory control via increased vagal tone is proposed to activate feedback and feed-forward circuits that re-condition autonomic reactivity across contexts (e.g., off the yoga mat), similarly described in the neurovisceral integration model of allostasis (Thayer and Lane, 2000; Thayer and Sternberg, 2006). Such neurovisceral integration is believed to dampen the release of neurochemical mediators (i.e., "stress hormones") across brain and bodily systems in an adaptive controlled process that extinguishes the prolonged sympathetic arousal and associated cognitive and emotional dysregulation that is habitually conditioned as a response (Thayer and Sternberg, 2006).

Another integrative tool for yoga's role in self-regulation is proposed to function through its increased attention to afferent information and emphasis toward processing bottom-up information. This shift is thought to alter integration between the bottom-up and top-down processes and can be described from an interoceptive predictive coding framework (Seth et al., 2011; Seth, 2013). Briefly, according to this framework, goal-directed or inferred states result in the top-down generation of predictive models of interoceptive signals. These models are then compared to the actual afferent bottom-up input, resulting in a prediction error that describes the difference between the top-down prediction and the bottom-up input. This prediction error can then be resolved either through active inference which includes changing the environment through motor and autonomic control, or through perceptual inference, which entails updating the model to accommodate the afferent input (Seth, 2013). If this prediction error would get resolved by active inference, matching afferent input would be generated and the conditioning would be maintained, while perceptual inference would result in extinction. Greater precision of afferent signals as the result of increased sensory attention, leads to perceptual inference. Yoga is proposed here to facilitate perceptive inference and thereby lead to extinction of maladaptive behaviors as described above.

A natural outcome of yoga practice has been demonstrated to be increased cardiovascular tone, musculoskeletal strengthening, balance and flexibility (see Yoga-facilitated output of **Figure 1**), benefits that may relate directly to the exercise component of practice (Ross and Thomas, 2010). In fact, many studies of yoga employ exercise as a comparison group (Ross and Thomas, 2010; Streeter et al., 2010), inferring that yoga may improve mental health at least in part via similar mechanisms as does exercise. The aerobic component of yoga practice facilitates beneficial changes in hemodynamic, hormonal, metabolic, neurological, and respiratory function (Ross and Thomas, 2010). These positive changes are the result of bottom-up mechanisms that increase metabolic efficiency of oxygen by the brain and body and maximize cardiac output (the volume of blood ejected by the heart per minute, which determines the amount of blood delivered to the exercising muscles; Fletcher et al., 1996). Ross and Thomas (2010) report in their review of 12 existing studies that yoga has been shown to be as effective or superior to exercise on nearly every outcome measured in healthy individuals (Ross and Thomas, 2010). There is some evidence that yoga postures may specifically improve symptoms of depression, stress, and anxiety (see Field, 2011; Li and Goldsmith, 2012). The influence of related physical exercise on psychological well-being has been fairly well-established (Hassmen et al., 2000; Penedo and Dahn, 2005), while the relationship between physical fitness and self-regulation is less clear. Although it remains unclear how yoga specifically differs from exercise, we hypothesize that postures in parallel with cardiovascular challenge may lay an essential foundation of implicit regulation on the yoga mat, facilitating increased vagal tone and equanimity during increased cardiovascular tone off the yoga mat.

In summary, based on existing research on stress modulation and conceptual understandings by which yoga is intended to function, we propose a model (**Figure 1**) that may influence self-regulatory systems in the context of physical and emotional stress that involves high-level and low-level brain networks and the associated top-down and bottom-up processes. This systems network model includes the major limbs of yoga, represented as a skillset of four process tools: ethics, meditation, breath regulation, and sustained postures. As depicted in the model, cognitive, emotional, behavioral, and autonomic output in response to a stressor is modulated by a number of regulatory processes (yellow boxes) proposed to be influenced by the process tools (limbs of yoga, blue boxes). A stress response is often accompanied by cognitive, emotional, and behavioral output that includes emotional reactivity, negative appraisal, and rumination (Chrousos and Gold, 1992a). In addition, autonomic output such as vasoconstriction, pain and/or tension, and inflammation often accompany maladaptive stress responses (Chrousos and Gold, 1992a; see solid black arrows). In chronic forms of such stress responses, negative, long-term consequences on health across bodily systems are often the result. Our model proposes that yoga facilitates adaptive output (dotted lines), including long-term psychological and physical well-being, musculoskeletal strengthening, and prosocial behavior, through four primary factors in the context of stress: (1) an emphasis on interoception and bottom-up input, (2) more efficient bidirectional feedback and integration with top-down processes, (3) increased phasic inhibition (red lines) of maladaptive forms of emotional, cognitive, and behavioral output (e.g., reactivity, negative appraisal, rumination) as well as autonomic output (e.g., vaso- and pulmonary constriction, inflammation, and muscle tension/pain), and (4) perceptual inference rather than active inference for improved prediction and error correction processes. These four factors optimize self-regulation and improve the communication and flexibility by which top-down and bottom-up processes inform behavioral output in the context of physical and emotional stress. Through repeated yoga practice, there is a resulting skillful optimization of autonomic control in response to stressors on and off the yoga mat – keeping arousal at lower levels during stress-mediated challenge, maintaining positive appraisal and reinforcement, helping the practitioner stay relaxed with less effort, and facilitating rapid recovery of bodily systems under stress. A number of cognitive, emotional, behavioral, and autonomic mechanisms are proposed along with the underlying high- and low-level brain networks that support such mechanisms.

A central executive network supports top-down mechanisms of attentional control and working memory allowing stable engagement with appropriate exteroceptive/interoceptive input for proper goal-directed behavior followed by self-correction if needed. A FPCN supports executive monitoring, meta-awareness, reappraisal, and response inhibition mechanisms. A moral cognition network supports positive forms of re-appraisal, as well as motivation and intention setting associated with self-care and prosocial behavior. The dorsal attention network helps to support attentional orienting, and engagement. HPA axis communication with brainstem vagal efferents support parasympathetic control, diaphragm strengthening, and homeostasis across systems. A striatopallidal–thalamocortical network is responsible for facilitating extinction learning and reconsolidation of maladaptive habits into behavior that is aligned with intentions and outcomes into adaptive habits.

EMPIRICAL EVIDENCE FOR THE PROPOSED MODEL AND THAT YOGA PROMOTES SELF-REGULATION ACROSS COGNITIVE, EMOTIONAL, BEHAVIORAL, AND AUTONOMIC DOMAINS

The theoretical model described above suggests that yoga practice may have salutary effects on self-regulation of cognitions, emotions, and behaviors through myriad pathways. Although this model is quite thorough and integrates knowledge across historical and contemporary theories of yoga and the current scientific literature associated with self-regulation, the empirical study of their linkages is sparse at this time. Below, we report the extant observational and intervention studies that have examined associations between yoga practice and self-regulation in a variety of populations.

EVIDENCE THAT YOGA AIDS IN COGNITIVE REGULATION

There is growing scientific evidence that yoga practice has an effect on cognition and processes underlying its regulation. For example, several studies have examined whether yoga can improve attention in children and adults. Ten days of uni-nostril or alternate nostril breathing resulted in increased spatial memory in children (10–17 years; Naveen et al., 1997). Adults showed improved performance on the letter-cancelation task after right and alternate nostril breathing (Telles et al., 2007). Kapalabhati and breath awareness have recently been shown to reduce optical illusion (Telles et al., 2011). An early randomized controlled trial of 14 children diagnosed with attention deficit hyperactivity disorder (ADHD) and on medication compared 20 sessions of yoga to an active control group, finding that those in the yoga group improved more in parent-rated ADHD scores (Jensen and Kenny, 2004). More recent studies of children with ADHD or attention problems have also shown positive effects (e.g., Harrison, 2004; Peck et al., 2005; Haffner et al., 2006). Studies have shown that memory and concentration increase in groups other than children with ADHD as well. One study found improvement in memory in Brazilian military recruits who participated in yoga as well as exercise compared to recruits in an exercise-only condition; effects were particularly strong for those under stressful conditions, but the improved memory persisted at a 6 month follow-up (Rocha et al., 2012). A study of adolescents found that a 7-week yoga program improved memory and concentration (Kauts and Sharma, 2009), and a study demonstrated acute improvement on speed and accuracy in math computations in a sample of 38 adults who participated in a 20-min Tai chi/yoga class; the authors attributed the improvement to the observed increased relaxation in the sample, although they did not test for mediation (Field et al., 2010). On a more physiological level of bottom-up sensory processing, an EEG study revealed decreased P300 latency following alternate nostril breathing and increased P300 peak after breath awareness in an auditory discrimination task. These findings were interpreted as decreased time needed for discrimination and increased availability of neural resources respectively (Joshi and Telles, 2009). A recent fMRI study with older adults found that age related decline in fluid intelligence was off-set in long-term yoga practitioners and that yoga practitioners had more efficient functional brain networks than carefully matched controls (Gard et al., 2014).

Many of these preliminary studies demonstrate improved cognition and suggest increased integration between explicit and implicit processes that regulate such cognitive and perceptual abilities. It should be noted that not all studies have found positive effects of yoga on cognitive regulation in either acute (e.g., Telles et al., 2012) or long-term yoga interventions (e.g., Chaya et al., 2012). In general, the literature testing the effects of yoga on cognitive regulation effects is preliminary, with small samples and lack of appropriate control groups. However, these initial findings are consistent with the notion that yoga can aid in better cognitive regulation.

EVIDENCE THAT YOGA AIDS IN EMOTION REGULATION

Literature demonstrating yoga's effects on emotion-regulation strategies is limited, but accumulating, both for acute (i.e., immediately following a yoga practice) and longer-term outcomes. One study examining the acute effects of a single yoga session on healthy women found that relative to a control group (who concentrated on reading a newspaper), women who experienced a yoga session reported less emotional lability, excitability, and aggressiveness. Further, they reported a lower tendency to cope with stress through aggression and self-pity and a higher tendency to cope through downplaying (reappraising) a situation (Schell et al., 1993). A yoga intervention with college students demonstrated that yoga increased students' self-compassion and emotion regulation skills (reductions in the difficulty with emotion regulation scale) and increased non-judgmental self-reflection (Sauer-Zavala et al., 2012). Similarly, in an adolescent sample, preliminary trends indicated that yoga during physical education may improve emotion regulation strategies relative to physical education-as-usual, perhaps through increasing emotion awareness (Noggle et al., 2013).

Yoga practice may also improve cognitive reappraisal (Garland et al., 2011), a form of emotion regulation that involves an ability to change the trajectory of an emotional response by reinterpreting the meaning of the stimuli. In a recent study, practitioners of Sudarshan Kriya and related practices (SK&P) were presented aversive pictures and asked to cognitively change their appraisal of the affective meaning of them by coming up with an alternative more positive interpretation of each picture. Relative to a non-yoga-practitioner control group, long-practicing yogis demonstrated a longer-lasting change in reduced magnitude of P300 event-related and late-positive potentials, indicating greater emotion regulation (Gootjes et al., 2011). Furthermore, Sudarshan Kriya has been reported to be beneficial for the treatment of depression, anxiety, stress, and post-traumatic stress disorder (for a review see Brown and Gerbarg, 2005a).

In addition to yogic breath regulation, yoga postures may also influence emotion regulation at a more physiological level. Breathing patterns of rapid inhalation and slow exhalation at an overall reduced respiration rate has been shown to decrease heart rate, skin conductance, and psychological arousal in a threatening situation (Cappo and Holmes, 1984). Preliminary data investigating different asanas on peripheral physiology suggests that basic body posture (spinal flexion, extension, or neutrality) may influence psychophysiological reactivity to interoceptive threat, possibly depending upon affective context (Wielgosz et al., 2012).

EVIDENCE THAT YOGA AIDS IN BEHAVIORAL REGULATION

A small amount of research suggests that yoga can help in behavioral regulation. One recent study found that a 10-week, twice-weekly yoga intervention with previously inactive participants increased their longer-term adherence to a physical activity regimen, indicating that yoga can boost one's ability to regulate a fairly difficult behavior, adherence to physical activity (Bryan et al., 2012). Another recent study of first- and second-year medical students enrolled in an elective yoga and mindfulness course showed that goal-directed regulation of behavior improved pre- to post-, according to self-report (Bond et al., 2013).

Investigations of nicotine addiction have shown that yoga may positively influence behavioral regulation. A study of women in cognitive–behavioral treatment for smoking cessation compared a yoga therapy condition to a general health and wellness program control condition. Women receiving yoga had higher 7-day smoking abstinence rates than controls at the end of the intervention, and abstinence remained higher among yoga participants through the 6 month follow-up (Bock et al., 2012). This increased behavioral control may be at least partly due to decreased cravings. Another study found that daily smokers assigned to either a brief yoga intervention or an exercise intervention, relative to a passive control, reported a decrease in craving to smoke. Further, while the exercise group reported lower craving in response to smoking cues, those who had received yoga reported a general decrease in cravings (Elibero et al., 2011). Although few in number, these studies are consistent with the notion that yoga may be useful in facilitating long-term regulation of behaviors that require considerable self-regulation, such as physical activity or smoking abstinence.

Yoga dose (amount, frequency, length of practice) may also be important for behavioral regulation. In a convenience sample of yoga practitioners, the amount of yoga practiced was modestly and inversely related to the use of dysfunctional coping, a coping style characterized by disengagement, venting, and substance use, suggesting that yoga may help to mitigate dysfunctional coping behavior (Dale et al., 2011). In a small sample, a yoga workshop increased participants' ability to recognize and respond to emotional states and to reduce mood instability, impulsivity, recklessness, and self-destructive behaviors (Dale et al., 2009).

CONCLUSION

There is emerging evidence from the extant literature to support the beliefs that modern adaptations of yoga practice are beneficial for mental and physical health. Here, we delineate very specific components of yoga practice (ethics, postures, breath regulation, and meditation) that are rooted in a historical framework and employed in varying degrees in contemporary contexts as a model for understanding how yoga may achieve its benefits – facilitating self-regulation and resulting in psychological and physical well-being. Beginning with a brief scholarly perspective of yoga history and philosophy, we present the core psychological, cognitive, and neuroscientific understandings of yoga in the context of a spectrum of physical and mental stress. Our proposed framework and systems network model integrates a great deal of theory and research regarding both bottom-up and top-down self-regulatory processes and the ways through which yoga may contribute to self-regulation across cognitive, emotional, behavioral, and physiological domains. Yet, we acknowledge that we were not able to capture all the likely relevant dimensions.

In summary, we propose that yoga practice facilitates self-regulation via an ethically motivated monitoring and control process that involves initiation and maintenance of behavioral change as well as inhibiting undesired output by both higher-level and lower-level brain networks in the face of stress-related physical or emotional challenge. We propose yoga practices emphasize a shift toward bottom-up interoceptive processing and the integration of self-regulatory bottom-up and top-down processes across bodily systems (including cardiovascular, neuroendocrine, and musculoskeletal). Particular mechanisms from high-level brain networks are proposed, including intention/motivational goal setting, attentional control, meta-awareness, response inhibition, working memory, and cognitive reappraisal; mechanisms from low-level brain networks are also proposed, including parasympathetic control, improved baroreceptor functioning, increased vagal tone, strengthening of the diaphragm, extinction learning, and early forms of attentional orienting and engagement. The mechanisms described provide a working model that integrates autonomic, cognitive, behavioral, and affective processes into a multi-systems framework for adaptive functioning, all of which serves to promote acute and long-term effects on well-being and mental and physical health. Through practice on the yoga mat, the proposed mechanisms are likely to be more successfully generalized into individuals' lives off the mat, equipping the practitioner with skills to enable adaptive autonomic nervous system functioning, and cognitive–emotional–behavioral processes that are more flexible and adaptive to emotional and homeostatic perturbations throughout daily life.

FUTURE DIRECTIONS

This framework serves as a starting point for understanding the growing research findings linking yoga with psychological and physical well-being, prosocial and ethical behavior, and musculoskeletal strengthening in terms of self-regulation. While it is promising that the framework accommodates current research findings, systematic testing of it is still required. As a result, and in line with our aims, the framework proposed is suitable to guide future research. Where possible, we have presented empirical literature examining the hypothesized links. However, for many of these links, very little research is available and much theory remains speculative. Although a sizable literature links yoga practice with psychological health, few studies have assessed mediators of the effects of the individual components of yoga on psychological health or examined how yoga practice in general affects self-regulatory processes.

Future research may elaborate on specific process tools and process outcomes that we propose improve the efficiency and adaptive nature of habitual forms of cognition, emotion, and behavior across systems of mind–brain–body functioning at both top-down and bottom-up levels. For simplicity, in **Figure 1** we did not map relative contributions of process tools onto process outcomes. For example, parasympathetic activation may be heavily influenced by breath regulation, but also to lesser degrees by sustained postures and meditation; and these influences may change depending on the particular techniques used and an individual's psychological and physical state. Furthermore, the influence of yogic tools on several of the process outcomes proposed in this model has not been directly studied.

Future studies should go beyond cross-sectional designs (e.g., novice vs. long-term practitioners) and focus on longitudinal designs with appropriate active control designs in order to rule out the multitude of potential third variables underlying someone's status as a long-time practitioner, and whether those aspects that differentiate long-term practitioners mediate any noted improvements in psychological well-being. Development of a testable online yoga research database analogous to BRAINnet's use of Brain Resource International Database (http://www.brainnet.net/about/brain-resource-international-database/) may afford such long-term needs especially with a focus on tracking people over time.

Yoga research is made more complex because of the many different process tools ("limbs"), each of which may have differential effects on various forms of self-regulation. Effects of some process tools have been minimally studied. For example, we were able to find only one study that examined the effects of explicit inclusion of *yamas* and *niyamas* in a yoga intervention (Smith et al., 2010). The need to assess the different contributions of particular process tools of yoga and to examine their unique contributions to outcomes is recognized among yoga researchers (e.g., Sherman, 2012). Toward this end, one group of researchers has been developing a new instrument with which yoga researchers can describe their interventions on key dimensions such as challenging asana, restorative asana, meditation, breathwork, spirituality, ethical principles, etc. (Park et al., 2014). Once completed, this instrument may provide the necessary quantification of yoga's various components to allow researchers to examine the unique effects of each on self-regulation. However, it may be that some of yoga's most potent effects on self-regulation are due to a synergy of multiple process tools of yoga, rendering dismantling studies of yoga practice potentially less useful for understanding its impacts on self-regulation. Yoga practice may be particularly helpful in promoting self-regulation for certain populations or conditions (e.g., major depression, ADHD, chronic pain; see Balasubramaniam et al., 2012) with known abnormalities in CNS and/or behavior that may allow for more targeted testing of the components of this model; this notion reflects the yogic perspective of the practice of meeting people where they are. In addition, different components of yoga practice may be better suited for different people, depending on individual differences. Such issues remain to be explored within the context of self-regulation and may be important components to include in recommended complexity-based analyses.

Such synergetic effects may also be non-linear requiring more sophisticated analyses that capture such complexity. For example, studies that employ non-linear dynamical models of self-organization and emergence may capture not only the integration of top-down and bottom-up neurological processes involved in the proposed self-regulatory mechanisms of yoga, but also the dynamic relationships of these processes to psychosocial and clinical outcomes (Pincus, 2012). Study designs that incorporate measures of heterogeneity, such as parsimony phylogenetics to define randomization groups and pattern or network analysis instead of analysis of averages, may respectively result in stronger comparison groups and more accurate representation of results than traditional randomized controlled trial designs (Abu-Asab et al., 2012). For example, in a study of tai chi in older adults with peripheral neuropathy, a complexity measure of postural control based on multiscale entropy analysis was able to detect significant changes that were correlated with improvements in function as opposed to linear analyses of traditional outcomes which failed to detect these changes (Manor et al., 2013).

An additional, important dimension that requires further elaboration includes social outcomes of yoga practice, such as the prosocial behavior briefly referenced in this paper, as well as social influences on self-regulation. Team sports and exercise literature suggests that group identity can influence motivation and consistency of practice (Fraser and Spink, 2002; Emmons et al., 2007). Given that much of modern yoga practice occurs in a group setting, it follows that similar influences of group identity on behavioral self-regulation may occur. Yet distinct from exercise, yoga may foster internalized experiences of physical activity within a group setting, whereas exercise (and most other social interactions) may orient more externally using extensive verbal and visual body language cues. Not only is a thoughtfully developed social process of this model needed, but it may also help inform the best types of control groups in future studies of yoga. Especially when studying social and behavioral aspects of our model of self-regulation, a mixed methods design approach may be helpful. Systematically capturing both qualitative data on participant experiences and quantitative data on mechanisms and outcomes, and then rigorously integrating the analysis and interpretation of these different data streams, may, for example, allow novel insights into the heterogeneity of response from a complexity analysis or a deeper understanding of those who may be more responsive to a particular yoga treatment than others.

We are hopeful that our model will prove useful to researchers examining the multiple systems through which yoga can affect self-regulation. It is clear that yoga practice has both top-down and bottom-up effects and a better understanding of these pathways and their integration will provide important advances in our understanding of human functioning as well as promote more effective interventions for improving human health and well-being.

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Neurophysiological and neurocognitive mechanisms underlying the effects of yoga-based practices: towards a comprehensive theoretical framework

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During recent decades numerous yoga-based practices (YBP) have emerged in the West, with their aims ranging from fitness gains to therapeutic benefits and spiritual development. Yoga is also beginning to spark growing interest within the scientific community, and yoga-based interventions have been associated with measureable changes in physiological parameters, perceived emotional states, and cognitive functioning. YBP typically involve a combination of postures or movement sequences, conscious regulation of the breath, and various techniques to improve attentional focus. However, so far little if any research has attempted to deconstruct the role of these different component parts in order to better understand their respective contribution to the effects of YBP. A clear operational definition of yoga-based therapeutic interventions for scientific purposes, as well as a comprehensive theoretical framework from which testable hypotheses can be formulated, is therefore needed. Here we propose such a framework, and outline the bottom-up neurophysiological and top-down neurocognitive mechanisms hypothesized to be at play in YBP.

Keywords: yoga, movement, breath, attention, allostatic load, basal ganglia, bottom-up, top-down

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Definition of Yoga-based Practices in the Context of this Paper

During recent decades numerous yoga-based practices (YBP) have emerged in the West. According to recent surveys, yoga is practiced by over twenty million people in the USA alone, with its status having evolved from a niche activity to the catalyst of a blooming multimillion dollar industry. Yoga is also beginning to spark growing interest within the scientific community, and a rapidly increasing number of studies are investigating the effects of yoga on physiological parameters, perceived emotional states, and cognitive functioning (Gard et al., 2014a). At the same time, the recent "yoga boom" has been met with controversy, especially when it comes to defining yoga in modern contexts. For example, in the West yoga has become virtually synonymous with posture or movement-based practice (Feuerstein, 2003). However, this type of practice is a relatively recent phenomenon, and according to some sources there is little evidence that movement-based practice has ever been the primary aspect of any ancient Indian yoga tradition (Singleton, 2010).

In its traditional sense, yoga is considered a spiritual practice with roots in the Yoga Sutras of Patanjali of which there are numerous interpretations and translations (Satchidananda, 1978; Hariharananda Aranya, 1983; White, 2014). In the context of these texts, the various components of yoga such as "asana", "pranayama", and the "samyamas" refer to postural, breath-based and meditative practices aimed at directing and refining "prana" (subtle energy or life force), with the ultimate goal of reaching a state of "samadhi" (an evolved state of the human spirit often referred to as pure consciousness). Since our aim is, however, to provide a secular and operationalized definition of YBP that is useful within our current and more limited Western scientific paradigm, we will largely refrain from the use of yogic terminology in this paper. Similarly, we will not focus on yoga from the perspective of a specific lineage, but instead outline a framework for YBP as modern psychophysiological therapeutic practices that employ a series of movement-, breath- and attention-based techniques inspired by a variety of yogic traditions. The main goal of YBP in this context is to optimize health, promote stress reduction and increase self-regulation, from both a prevention and treatment perspective. We suggest that science can contribute by operationalizing the components and carefully evaluating the efficacy of YBP, for the purpose of furthering an evidence-based understanding of their effects and of promoting their integration into mainstream medical practice. In addition, a science-based understanding of YBP can help elucidate the mechanisms that underlie the effects of YBP, so that they can be precisely tailored to target the specific needs of different populations.

In the following sections of this paper we will: Provide a brief and critical review of a subset of the literature on YBP applied in non-clinical populations; Outline the main methodological shortcomings of previous studies and address some important considerations for future research in the field; Provide a detailed description of the main components of modern YBP that we believe need to be taken into account when designing and describing interventions; Outline the main neurophysiological processes and neural circuits we propose to be at play in and influenced by YBP.

Brief Overview of the Literature Investigating the Effects of Yoga-based Practices

Over the past decades there has been an exponential increase in publications on yoga related research (**Figure 1**). For the purpose of the current paper, we will review a specific subset of studies targeting healthy populations undergoing YBP protocols that involve at least some degree of posture and/or movement. Hence, studies on clinical populations and purely breath-based or meditative practices are not included. We will summarize what these previous studies suggest regarding the effects of YBP on physiological parameters, body awareness, self-reported emotional states and stress, and cognitive functioning.

Physiological Parameters

Only a small number of studies on healthy populations have investigated the effects of YBP that include postures or movement on physiological parameters such as stress hormones, inflammatory markers and cardiovascular indices.

One of these studies (Rocha et al., 2012) compared salivary cortisol levels in two groups of military populations who underwent 6 months of either yoga or regular physical exercise. Following the program, the yoga group showed significantly lower cortisol levels than the exercise group, but the results must be cautiously interpreted as they are based on a single cortisol sample collected pre and post intervention. In addition, the yoga intervention is only vaguely described as a combination of asana, pranayama, and meditation. Another study (Kamei et al., 2000) involving electroencephalography (EEG) recordings and serum cortisol measurements, found an increase in frontal alpha rhythm and decrease in cortisol after a single yoga session. However, it should be noted that the experimental group was comprised of self-selected yoga teachers who were not compared against a control group. Moreover, the yoga session was not described in sufficient detail to allow for replication of the study.

A study using magnetic resonance spectroscopic imaging (MRSI; Streeter et al., 2007) investigated the effect of a single hour of yoga practice on y-aminobutyric acid (GABA) levels. In an experimental group of experienced yoga practitioners, GABA levels were measured before and after an hour of yoga practice, whereas in a control group of yoga novices, GABA levels were measured before and after an hour of reading. Only the experimental group showed a significant increase in GABA levels, which the authors interpreted to suggest that yoga may be effective for treating disorders associated with low GABA levels such as depression, anxiety and epilepsy. The study was weakened, however, by a lack of random assignment, unmatched interventions, different levels of yoga experience between group participants, as well as an insufficient description of the yoga protocol.

Parshad and colleagues (Parshad et al., 2011) measured a series of cardiovascular indices before and after a 6 week yoga program. The experimental group was a self-selected cohort of medical students enrolled in a yoga course for stress management, and there was no control group. The results indicated reduced total peripheral resistance (TPR), as well as increased arterial compliance (CWK), stroke volume (SV) and cardiac output (CO). Lastly, a pilot study measuring blood pressure (BP) and heart rate variability (HRV) in twelve healthy adults before and after an 8 week yoga program (Papp et al., 2013), found a significant increase in HRV which was interpreted to suggest that yoga promotes increased vagal tone and reduced sympathetic activity. While this interpretation is warranted, the study calls for replications with larger sample sizes and the inclusion of control groups.

Body Awareness

Body awareness is a multi-dimensional construct that entails a combination of proprioceptive and interoceptive awareness (Mehling et al., 2012). Since most types of YBP emphasize

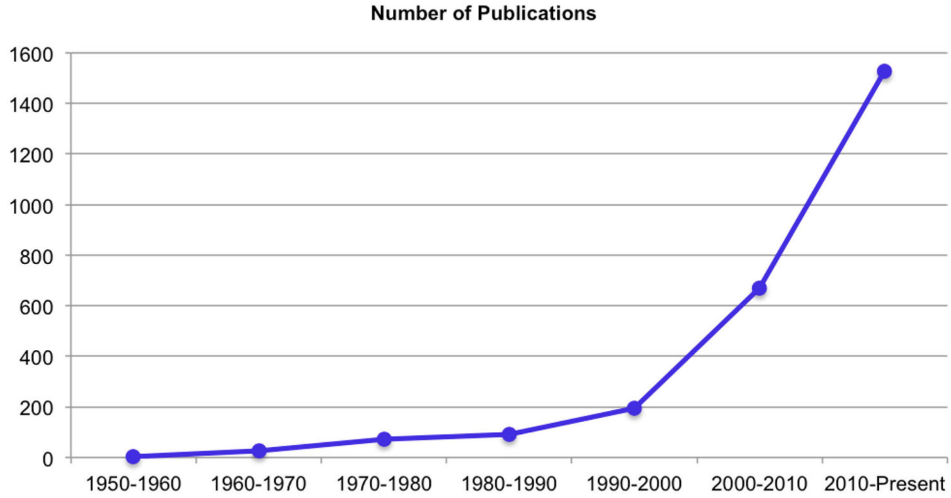

FIGURE 1 | Increase of yoga related publications over the past decades—PubMed search performed in March 2015 for articles with the term yoga in the title, abstract or keywords.

attention to proprioceptive and interoceptive signals, it can be hypothesized that they are an efficient method for fine-tuning body awareness. However, so far only a few studies have directly investigated this potential effect of YBP.

An early study (Rani and Rao, 1994) compared self-reported body awareness as assessed by the Body Awareness Questionnaire (Shields et al., 1989) from individuals who completed a 3 months long yoga program, to entering enrollees of the same program. Though participants who finished the program reported greater body awareness, no pre-post comparisons were done. In addition, the yoga program was insufficiently described as involving a daily asana and pranayama practice.

More recently, David and colleagues (David et al., 2014) assessed body awareness in relation to susceptibility to the rubber hand illusion in advanced yoga practitioners and controls with no yoga experience. On average, yoga practitioners scored significantly higher on the Body Perception Questionnaire (Porges, 1993) than control subjects, but self-reported body awareness did not correlate with performance on the rubber hand illusion experiment. A further study from the same laboratory (Fiori et al., 2014) assessed proprioceptive and vestibular body signals, as well as the presence of self-transcendence (ST) traits in a group of advanced yoga practitioners and controls with no yoga experience. The processing of body signals was assessed via the Rod and Frame Test (RFT; Asch and Witkin, 1948), and ST was measured with a sub-scale of the Temperament Character Inventory (TCI; Cloninger et al., 1994). Overall, yoga practitioners showed higher accuracy in the RFT and higher ST scores on the TCI. The findings were taken to suggest that yoga practitioners have a higher degree of body awareness that may be related to aspects of ST.

Lastly, indirect evidence for the effect of YBP on body awareness comes from a recent study (Villemure et al., 2014) using sensory testing as well as neuroimaging techniques (voxel-based morphometry and diffusion tensor imaging) to investigate the neuroanatomical underpinnings of pain detection and pain tolerance in yoga practitioners and controls with no yoga experience. Although yoga practitioners did not have a higher pain detection threshold, they tolerated pain (as measured by the length of time they kept their hand in cold water) more than twice as long as controls. Yoga practitioners also had more gray matter volume (GMV), expressed as percent of total intracranial volume, in a number of regions including the insula, cingulate cortex, medial prefrontal cortex, inferior and superior parietal lobule, as well as increased intra-insular white matter connectivity. Moreover, insula GMV correlated positively with pain tolerance (left and right insula) and years of yoga practice (left insula only). Self-reports of strategies used to tolerate the pain revealed that yoga practitioners used much more "embodied" approaches (e.g., focusing on the breath, attending to the sensation, observing the pain without reacting etc.) compared to controls (e.g., trying to ignore the pain and distract oneself). Taken together, these findings suggest that increased pain tolerance in experienced yoga practitioners may be a consequence of adaptive insular changes, mediated by increased parasympathetic activity and interoceptive processing.

Self-Reported Emotional States and Stress

Self-reports of emotional states and stress are a frequently used outcome measure in research on YBP (Riley and Park, 2015).

An early study (Wood, 1993) measured self-reported levels of vitality (e.g., perceived levels of alertness, sleepiness, enthusiasm, sluggishness, calmness, nervousness etc.) in a gentle form of yogic movement and breathing vs. relaxation or visualization techniques. Over a period of 2 weeks, participants took part in two sessions of each modality, and vitality was measured via visual analog scales immediately before and after each session. The yoga practice session yielded higher levels of self-reported vitality, but given the limited number of sessions and the insufficient description of the intervention, the conclusions are not broadly applicable. Self-reported wellbeing as measured by the Subjective Well-Being Inventory (Sell and Nagpal, 1992), was assessed in a self-selected group of health care practitioners who underwent a 4 months long yoga program consisting of five one-hour yoga classes per week (Malathi et al., 2000). Though the participants reported increased levels of well-being by the end of the program, there was no control group to rule out external factors that may have promoted the effect.

A more recent study (Gard et al., 2012), looked at self-reported perceived stress (as well as other psychological outcome measures) in attendees of a 4 months long residential yoga program described as daily sessions of asana, pranayama and meditation, as well as didactic course work focusing on the integration of yoga practices into daily life activities. Compared to a control group of individuals not participating in the program, attendees exhibited lower levels of perceived stress measured with a 10-item version of the Perceived Stress Scale (PSS; Cohen et al., 2009), statistically demonstrated to be mediated by increased levels of mindfulness and self-compassion. The authors appeal to existing models used to explain how mindfulness affects wellbeing (Shahar et al., 2011), but do not offer specific hypotheses of additional/alternative mechanism directly related to their yoga-based intervention.

Lastly, in their study with military populations participating in a 6 months yoga program mentioned above, Rocha and colleagues (Rocha et al., 2012) documented reduced levels of self-reported depression, anxiety and stress.

Cognitive Functioning

To conclude this brief literature review we will look at studies investigating the impact of YBP on cognition including attention, memory and executive functioning.

One study looking at the effect of a 10 day long residential yoga program on visual attention (Telles et al., 1995), found that overall the experimental group improved in their ability to detect flicker frequencies, whereas a control group who did not participate in the program showed no improvement. These results were taken to suggest that yoga may hone one's ability to detect subtle changes in visual stimuli, but there is not enough reported detail about the yoga intervention to inform an understanding of which aspect of the yoga practice may have promoted improvement in visual attention. Another study on visual attention (Narayana, 2009) found faster reaction times on a visual color discrimination task in yoga practitioners compared to a group of non practitioners. The findings were attributed to increased alertness and visuo-spatial attention promoted by the yoga practice, yet again the insufficient detail about the yoga protocol prevents an interpretation of the causative factors driving the results. In addition, the experimental and control groups were not matched for size (26 vs. 42 participants), which makes the findings vulnerable to interpretative error.

In regard to memory, Gothe and colleagues (Gothe et al., 2013) found greater improvements in working memory in novice practitioners after a single session of yoga compared to a single session of general aerobic exercise. Improvements in both short-term and long-term memory were also reported in the study on military populations by Rocha and colleagues mentioned previously (Rocha et al., 2012).

As for executive functioning, one study (Manjunath and Telles, 2001) reported improvements in problem solving ability in a group of female school children after 7 days of yoga practice, compared to a group of children performing the same amount of regular physical exercise. Specifically, the children participating in the yoga classes were reported to have come up with more efficient solutions (planning time, execution time and number of moves) on the Tower of London Task (Shallice, 1982). As for most of the previous studies, there are insufficient details about the yoga intervention to draw any conclusions about what might have yielded the problem solving improvements. Another study (Oken et al., 2006) assessed alertness and executive functioning as part of a battery of physical, psychological and cognitive assessments, in over 100 seniors randomly assigned to a yoga, exercise, or wait-list control group. The intervention took place over 6 months, with one led class per week complemented by home practice. Alertness was assessed via quantitative electroencephalogram measurements (EEC), and executive functioning was assessed with the Stroop Task (Stroop, 1935). While no group differences were detected in either outcome measure, the study has to be credited for a well-powered, randomized, and controlled design, as well as a detailed description of the yoga intervention. The authors argue that their findings may be due to ceiling effects, and maintain it is still likely that yoga can positively affect cognition.

More recently, Froeliger and colleagues (Froeliger et al., 2012a) used voxel-based morphometric analyses to compare GMV in experienced yoga practitioners and controls with no yoga experience, and correlated GMV with self-reported errors on a Cognitive Failures Questionnaire (CFQ; Broadbent et al., 1982). On average, yoga practitioners exhibited greater GMV in frontal, limbic, temporal, occipital as well as cerebellar regions. In addition, they reported fewer cognitive failures on the CFQ, indicating fewer errors in attention, memory, and motor function in everyday tasks. Interestingly, increased GMV correlated positively with years of yoga practice, and negatively with self-reported number of cognitive failures on the CFQ. The authors concluded that yoga practice may promote neuroplastic changes in neural systems that support executive functioning.

Another study (Gard et al., 2014b) investigated age-related decline in fluid intelligence—i.e., a set of abilities involved in coping with novel environments and abstract reasoning (Sternberg, 2008)—as well as resting-state functional brain network architecture in experienced yoga and meditation practitioners. Compared to controls who had no experience with either of these practices, yoga and meditation practitioners had less age-related decline in fluid intelligence as measured by the Raven's Advanced Progressive Matrices (APM; Raven et al., 1998). They also had more resilient functional brain networks, as reflected by more resilience to attacks in the context of artificial neural network simulations (Achard et al., 2006), across cortical, subcortical and cerebellar regions. Both effects were primarily driven by the yoga group, but it has to be noted that the yoga practitioners had a much higher average number of lifetime practice hours than the meditation practitioners. Moreover, the authors acknowledge the potential confounding factor that individuals with higher fluid intelligence and better functional neural network integration might be more naturally inclined to practice yoga and meditation in the first place. Hence, further studies in which both the experimental and control groups consist of naïve participants are needed.

Lastly, functional magnetic resonance imaging (fMRI) was used to investigate the neurocognitive correlates of emotion interference on executive functioning in yoga practitioners and controls with no yoga experience (Froeliger et al., 2012b). Specifically, participants performed an Affective Stroop Task (Froeliger et al., 2012c) in an event-related design, in which the individual trials were bracketed by neutral or negative emotional distractor images. Between groups there were no significant task-related behavioral differences, but there were interesting neural differences. It is known that while viewing negative stimuli, mid-frontal brain structures associated with executive cognitive control may activate to implement top-down modulation of negative affective responses (Wager et al., 2008). In yoga practitioners, prefrontal activation during negative emotion trials was greater compared to controls only during the presence of the cognitively demanding task, but not during the simple viewing of emotional stimuli *per se*. Moreover, in yoga practitioners amygdala activation to negative emotional distractors was not coupled with task-related changes in affect as measured with the Positive and Negative Affect Schedule (PANAS; Watson et al., 1988). These results suggest that yoga practitioners may be able to selectively recruit frontal executive strategies in response to emotionally salient stimuli as a function of cognitive demand. They also indicate that, as mindfulness-based practices (Hölzel et al., 2011), yoga may promote attention toward emotional stimuli without active attempts to cognitively restructure the affective experience.

Limitations of Previous Studies on Yoga-based Practices

The relatively small body of literature on the effects of YBP that involve posture and/or movement in healthy populations reviewed above, has several methodological limitations. Below we will list some of the main points of concern, and outline a number of key factors for the systematic investigation of YBP in the future.

Self-Selected Populations and Inappropriate Control Groups

In most of the aforementioned studies, the experimental group consisted of either advanced practitioners (David et al., 2014; Villemure et al., 2014) or individuals participating in a residential yoga program (Telles et al., 1995; Gard et al., 2012), whereas the control participants, were mostly individuals with no yoga experience. As pointed out by Gard and colleagues (Gard et al., 2014b), some of the reported physiological or behavioral differences may be driven by pre-existing characteristics of individuals who are naturally inclined to engage in YBP. Similarly, the effects of motivational and expectance factors of individuals who self-initiate interest in YBP need to be taken into account (Jensen et al., 2012). In addition, many of the studies did not include an active control group (Froeliger et al., 2012a; Fiori et al., 2014), and if they did it predominantly consisted of regular physical exercise (Oken et al., 2006; Gothe et al., 2013). This can be problematic since exercise matches YBP only in terms of overall physical demands and group participation in general. In order to broaden the evidence base for the effects of YBP it is important to conduct further studies on a larger variety of healthy and clinical populations. Studies with yoga naïve healthy participants will be particularly informative for determining the longevity and intensity of practice necessary to yield measurable effects. Individual characteristics such as body type, personality, motivation etc. that might influence a participant's response to the practice should also be more carefully assessed. A better understanding of the mechanisms of change and the individual factors influencing responsiveness in healthy populations, will in turn allow for more precisely targeted interventions in clinical populations. More studies including random assignment to either YBP or carefully matched active control conditions are necessary. Control conditions need to be matched to YBP not only for overall physical intensity, but also for more subtle factors such as specific attentional demands.

Use of Self-Report Outcome Measures Alone

Many of the studies assessing the effects of YBP on perceived levels of stress and emotional states have based their results on pre vs. post comparisons of self-report outcome measures alone (Wood, 1993; Malathi et al., 2000). This represents a problem when studying contemplative practices in particular, as the participants' perception and judgment of their own skills and coping mechanisms are often altered as a result of the practices themselves. Some of the inherent cognitive biases accompanying self-report assessment of intervention outcomes have been explicitly addressed in regard to mindfulness-based practices (Grossman, 2008), and we believe that similar concerns apply to YBP. Given the commonly touted positive effect of YBP for one's overall well-being, there is a danger of biased responses toward expecting, believing, and reporting that the intervention has worked. In future studies it will be important to more carefully develop and select outcome measures. Complementary assessment of behavioral, physiological, neural and cognitive change is necessary to obtain a comprehensive understanding of the effects. Studies combining both first person reports of experienced effects, and third person objective measurements thereof, will be particularly informative.

Poorly Described Interventions

With few exceptions (Oken et al., 2006; David et al., 2014), the descriptions of the YBP administered to participants lack the necessary details to allow for close experimental replication of the studies. In fact, in several cases the interventions are merely referred to as a combination of asana, pranayama and relaxation techniques (Rani and Rao, 1994; Narayana, 2009). Given that there are many variations of modern YBP, this is clearly problematic. Concerted effort needs to be directed toward accurately and sufficiently describing the exact type of movement, breath and attention that are being instructed in the context of a particular intervention. This is crucial for designing appropriate control conditions, as well as for the possibility to replicate the studies.

No Investigation of the Individual Components of YBP

YBP are inherently multifaceted in nature, typically involving a combination of specific postures or movement sequences, specialized use of the breath, and various techniques to promote sustained attention (Gard et al., 2014b). So far, little if any research has attempted to deconstruct the role of these different component parts. Hence, it remains unclear to which extent the movement, the breath or the attentional focus are driving the effect on the observed changes in physiology, emotional states and cognition, and whether the effect of these components is synergistic in nature (Payne and Crane-Godreau, 2013). To shed further light on the factors that drive the effect of YBP, an important avenue for future research studies is to attempt to disentangle the respective contribution of the individual component parts in more detail. Investigations in which the type, amount or intensity of either movement, breath or attention are carefully manipulated, while the other components are kept constant, will be particularly informative in this regard. Such studies will allow the investigation of which specific outcome measures are primarily impacted by each of the components.

Lack of Hypotheses About the Specific Mechanisms of Change Underlying the Reported Effects of YBP

While some studies outline hypotheses about neurophysiological and neurocognitive mechanisms underlying the results (Froeliger et al., 2012b; Gard et al., 2012; Villemure et al., 2014), these hypotheses mostly refer to general mechanisms known to underlie the effect of mindfulness-based practices. Other studies (Rani and Rao, 1994; Kamei et al., 2000; Malathi et al., 2000) don't provide any detailed mechanistic hypotheses at all. Recently proposed theoretical frameworks about the effects of YBP are an encouraging step forward (Gard et al., 2014a; Henje Blom et al., 2014a), but the proposed mechanisms have yet to be systematically tested in healthy populations. Future studies on YBP should be driven by specific hypotheses about the mechanisms of change that are being targeted. Hypotheses about the interaction between bottom-up physiological and top-down cognitive processes that can be systematically tested will be of particular relevance. Testing of such hypotheses will require multidisciplinary approaches across the domains of physiology, neuroscience and psychology.

The Main Components of Modern Yoga-based Practices

We will now outline and provide a detailed description of three fundamental components of modern YBP, namely movement, breath and attention. A deconstruction of these components is very important when designing and describing interventions aimed at better understanding their respective effects.

Movement

What constitutes "movement" in the context of movement-based contemplative practices is not necessarily easy to define, as it can range from large overt motion, to small subtle motion, and often even to purely internal or imagined motion (Schmalzl et al., 2014). Here we refer to movement in the sense of the overt execution of specific physical postures or movement sequences. This type of practice is very prominent in modern yoga, and there are many different schools that differ in the type of movement they entail. Some practices, such as Ashtanga Vinyasa Yoga (Jois, 1999), are characterized by quite intense and continuous physical motion with a focus on creating a "flow" of movement by linking one posture to the next. In other practices, such as Iyengar Yoga (Iyengar, 1966) or other forms of Hatha Yoga (Akers, 2002), the movement is less dynamic and the focus is on holding individual postures for a longer period of time. Independently of its historical origin (Singleton, 2010), the movement aspect of modern YBP has potentially important therapeutic implications such as physical/physiological benefits, fine-tuning of interoceptive and proprioceptive awareness, and providing a context for training attention. Below we will outline the types and characteristics of movement employed in modern YBP that sets it apart from more common forms of physical exercise.

Postures

Both static and dynamic forms of YBP involve the execution of specific physical postures. The postures are overall designed to increase range of motion, strength and flexibility. They are mostly taught using precise alignment cues, and depending on the type of practice they can be held for just a few breaths or up to a few minutes. There are innumerable individual postures and variations thereof that can be descriptively categorized into standing, seated, and supine postures, or into forward folds, backbends, hip-openers, twists and inversions.

Movement Sequences

When YBP involve dynamic movement sequences, these are often performed in a slow, rhythmic and symmetric fashion that is synchronized with the breath so as to create a flow from one pose to the next. The joint load is mostly kept at submaximal levels, which has been suggested to be beneficial for bone remodeling and osteogenesis (Omkar et al., 2011).

Interior Muscle Activations

Another common aspect of current posture practice across many yoga styles is the use of a static and soft contraction of interior muscle groups at the level of the pelvic floor, the lower abdomen and the throat. The activation of these muscle groups aids breathing practices and facilitates the maintenance of a strong core musculature while moving through the postures. Within some of the traditional yoga systems these muscle activations are referred to as "bandhas", and described as seals that can direct the flow of prana in the body.

Coordinated Movement of Moderate Intensity

YBP are mostly performed in a slow and controlled manner and require balance, coordination, as well as a constant tracking of the body's position in space. Postural alignment, fluidity and fine-tuning of the movement are emphasized. In contrast to many forms of physical exercise that tend to increase activity in the sympathetic nervous system, it has been proposed that the level of intensity employed in YBP is likely to increase parasympathetic tone and consequently promote down-regulation of stress levels (Larkey et al., 2009).

Expansion of the Range of Motion

In many yoga styles, posture practice is aimed at expanding range of motion. A common belief is that we "hold" tension in our muscular system, and that the accumulation of both physical and emotional stress over time manifests as stiffness and blockages in our muscles, joints and connective tissue. A putative aim of posture practice is therefore to release this tension by directing attention to the physical limitation, while directly moving towards and breathing into it. One may hypothesize that the reduction of experiential avoidance that comes with this type of practice may be generalized to other behaviors and increase psychological flexibility. This approach differentiates many YBP from other forms of movement-based contemplative practices such as qigong, which hold the view that approaching the limits of ones range of motion might actually increase tension and resistance, and consequently impede the flow of "qi" or energy (Cohen, 1999).

Tracking of Bodily Sensations

A fundamental aspect of YBP is paying attention to interoceptive, proprioceptive, kinesthetic and spatial sensations, and using that information to adjust and fine-tune one's movements. Interoceptive awareness refers to the awareness of internal bodily states and sensations, including heart rate, respiration, as well as several autonomic nervous system responses related to emotional states (Cameron, 2001). The importance of interoceptive awareness is manifold. In his theory of somatic markers, Damasio (Damasio, 1996) posits that interoceptive awareness is essential for most affective, cognitive as well as interpersonal processes. In fact, it underlies one's sense of affective and autonomic state, which is in turn fundamental for relating to the outer world (Damasio, 2000). The processing of bodily sensations is also a key for our sense of bodily self, which originates through the integration of interoceptive, proprioceptive, kinesthetic, tactile and spatial information (Ehrsson, 2007; Haselager et al., 2011; Ionta et al., 2011). Studies on tai chi as well as meditation techniques have shown that these practices can alter tactile acuity (Kerr et al., 2008), interoceptive accuracy (Fox et al., 2012), and in fact the cortical representation of interoceptive attention by impacting connectivity between the posterior and anterior insula (Farb et al., 2013). Recent evidence for increased pain tolerance in advanced yoga practitioners (Villemure et al., 2014), putatively mediated by adaptive insular changes and increased interoceptive processing, suggests that YBP may also promote similar effects.

Intent of Obtaining a State of Eutony

Lastly, yoga-based movement is practiced with the intent of obtaining a balanced muscle tone that allows the movement to feel stable and well rooted, yet light and effortless. While individual postures or parts of the practice may be characterized by a hypertonic (e.g., arm balances that require a high level of muscle tension) or hypotonic (e.g., a supine relaxation pose) state, the overall aim of the practice is to create a state of eutony or "well-balanced tension" (Alexander, 1985).

Breath

It is beyond the scope of this paper to explore the multitude of breathing practices found within different yoga traditions. We will instead simply outline the different ways in which breath awareness and conscious breath regulation are emphasized in the context of modern practices. In dynamic YBP there is often a focus on precisely coordinating the movements with the breath. In other types of YBP, the postures are sometimes maintained during breath retention, or the breath serves merely as an object of attention as in many meditation practices. The conscious practice of altering breathing patterns may have a number of different effects depending on their characteristics (Brown and Gerbarg, 2005a). For instance, slow and rhythmic breathing is said to promote a shift to parasympathetic dominance via vagal afferent stimulation with consequent stress reduction (Sovik, 2000), whereas more forceful breathing practices may promote sympathetic activation (Beauchaine, 2001).

In some systems, e.g., Ashtanga Vinyasa Yoga (Jois, 1999), each posture and movement sequence is coupled to a specific breathing rhythm so that specific movements help enhance the breath (and *vice versa*). For example, expansive movements (e.g., chest openers) facilitate inhalation, whereas contractive movements (e.g., forward folds) facilitate exhalation. In other types of practices the focus is simply on cultivating an even rhythm of inhalations and exhalations, with no specific emphasis on linking movement with breath. Practicing breath awareness and conscious breath regulation in the context of movement has the potential of facilitating the use of supportive breathing patterns in everyday life situations. The breath can also be harnessed as a tool to direct attention to specific body parts while holding a posture or performing a movement, and to consequently increase interoceptive and proprioceptive awareness. In addition, the breath can be used to "turn towards" unpleasant or stressful sensations that arise in the context of the physical practice, and to "breathe into them" rather than avoid or fight them.

One example of an often-used breathing technique in modern YBP is "ujjayi breath" (Brown and Gerbarg, 2005a). It is a deep, slow and rhythmic breath in which involves visualizing the inhalations starting from the lower belly, continuing in a wave through the ribcage, upper chest and throat, and subsequently the exhalations in the opposite order. Both inhalations and exhalations are performed through the nostrils with concurrent narrowing of the throat passage at the level of the glottis, which creates a soft and soothing sound. When ujjayi breath is performed during dynamic movement practice, inhalations and exhalations are ideally of equal duration. The duration is controlled by the diaphragm, and can gradually extend with practice. It is emphasized not to force or hold the breath, to avoid muscular tension.

Western science on respiratory physiology supports the view of some Eastern yoga traditions that emotional states are expressed in breathing patterns, and subsequently that voluntary change of the breathing patterns can alter emotional states and influence wellbeing (Boiten et al., 1994; Brown and Gerbarg, 2005a; Henje Blom et al., 2014b). In fact, a typical autonomic reaction to stressful situations is rapid thoracic breathing, which in turn leads to hyperventilation, altered tidal volume and hypocapnia (Laffey and Kavanagh, 2002). These symptoms are frequently observed as chronic manifestations in individuals with anxiety and depressive disorders (Meuret et al., 2004), and may be alleviated by the types of breathing techniques described above (Brown and Gerbarg, 2005b).

Attention

Regulation of attention is a central aspect of most contemplative practices, and YBP are no exception. We will first outline commonly used categories of attention from a cognitive science perspective. Subsequently, we will describe some more specific types of attentional focus and how they relate to YBP.

Commonly Used Categories of Attention

Though a variety of attention theories exist, one predominant characterization divides attentional processing into three main functional branches—alerting attention, orienting attention, and executive functioning (Posner and Boies, 1971; Fan et al., 2002, 2003). Each of these has been linked to distinct neural networks (Petersen and Posner, 2012). Alerting attention, also referred to as vigilance, sustained attention, or task-specific phasic alertness, refers to a general ability to track, and preparedness to respond to, environmental or task related stimuli (Raz and Buhle, 2006). In YBP, alerting attention is primarily recruited for tracking bodily sensations, which we will outline in detail below. Orienting attention involves active scanning of the environment or an array of stimuli, and subsequent orientation toward, or selection of, a specific target for the execution of a behavior or task. In YBP, orienting attention supports fine-tuning of neuromuscular feedback processing, and the consequent efficiency of muscle engagement for the execution of physical postures, movement sequences, and breathing techniques. Executive attention refers to the ability to selectively pay attention to relevant stimuli in our environment, while contemporarily inhibiting irrelevant information. In YBP, executive functioning is used to maintain attention on present-moment physical and mental states, while simultaneously withholding attention from irrelevant distractions.

Attention to Bodily Sensations

One of the principal defining characteristics of YBP, akin to other forms of movement-based contemplative practices (Schmalzl et al., 2014), is the emphasis on becoming increasingly attentive to bodily sensations and sensory experiences. This includes the cultivation of interoceptive, proprioceptive, kinesthetic and spatial awareness, while primarily paying attention to the movement and breath components of the practice described above. Such direct focus as a goal in its own right differentiates YBP from most other types of conventional exercise, where the goal is often external in nature (e.g., hitting a target, performing a specific action, reaching a destination etc.).

High degrees of body awareness have been associated with both negative and positive effects (Mehling et al., 2012). On the one hand, excessive focus on bodily sensations can be an indication of somatization, anxiety and even depressive symptoms. In this case, enhanced body awareness often takes on the form of hyper vigilance, rumination and over interpretation of bodily signals. On the other hand, there is increasing consensus that body awareness and the ability to detect subtle bodily cues can be beneficial for health and self-regulation. In this case, enhanced body awareness reflects an increased ability to observe bodily signals as such without getting caught up in them (Baas et al., 2004). One goal of training body awareness for therapeutic purposes is therefore to increase proprioceptive and interoceptive awareness, while reducing self-evaluative processes (Watkins and Teasdale, 2004). On a neural level this has been proposed to correlate with a shift from predominantly medial prefrontal activation, to increased activation of the thalamus, the insula and primary sensory regions (Farb et al., 2012). We hypothesize that compared to seated contemplative practices, the added movement component of YBP may increase the intensity of interoceptive and proprioceptive signals, and subsequently facilitate their processing and integration. Hence, YBP may offer a potentially even more efficient method for cultivating bodily awareness as well as general attentional skills.

Focused Attention vs. Open Monitoring

Contemplative practices use a variety of techniques to train focus of attention (Jha et al., 2007; Lutz et al., 2008; Manna et al., 2010). Meditation practices are often classified as engaging predominantly focused attention (FA) or open monitoring (OM) techniques (Lutz et al., 2008), and it is not yet well-defined where YBP fall on that spectrum. In short, FA techniques involve directing and sustaining attention on a single selected object (e.g., the sensation of the breath), whereas OM techniques emphasize non-reactive metacognitive monitoring of perceived sensory, emotional or cognitive events that may arise from moment to moment during one's practice.

In the context of mindfulness-based practices, it has been argued that while beginners tend to primarily engage in FA, advanced practitioners gravitate more toward an OM approach (Lutz et al., 2008). We propose that individuals engaging in YBP are also likely to gradually transition from a FA to a more OM attentional orientation. Novice practitioners may only be able to allocate their attention to one single element of the practice at the time, but as their practice advances they are likely to become increasingly skilled at simultaneously monitoring movement, breath, and any concomitant interoceptive and exteroceptive sensations that may arise. Hence, we hypothesize that YBP, at least in more advanced practitioners, primarily engage an OM type of attention.

Metacognitive Awareness

Metacognition can be broadly defined as the conscious and mostly intentional monitoring of our own mental processes and behaviors (Teasdale, 1999). The action of "stepping back" to observe ones own inner sensations and thoughts is central to most contemplative practices including YBP. It is also an aspect that differentiates YBP from many common forms of exercise, which are often practiced without a primary goal of paying attention to bodily or mental states (e.g., running on a treadmill while listening to music).

To our knowledge there are no studies that have directly investigated the effect of YBP on metacognition as such. Hence, we will refer to some insights from the literature on mindfulness-based practices, which may also apply to YBP. It has recently been proposed (Fox and Christoff, 2014), that alongside creative thought and lucid dreaming, mindfulness-based practices represent a third quite unique scenario of interplay between metacognition and so-called mind-wandering (MW), which refers to spontaneous and undirected thought processes that mostly occur without our volition (Kane et al., 2007). With reference to the FA vs. OM distinction addressed above, there are two broad possibilities for the co-existence of MW and metacognition. In the context of FA, metacognition has the "suppressive" function of noticing drifts of attention from a selected object, and subsequently of redirecting attention towards it. In the context of OM, metacognition has the more "integrated" function of monitoring one's stream of thought, while attempting to maintain detachment and refrain from any cognitive elaboration or judgment.

One proposed benefit of a consistent and non-judgmental metacognitive monitoring of sensations and spontaneous thought processes is reduced negative self-referential rumination (Deyo et al., 2009). Repeated practice of simply monitoring one's sensations and thoughts without trying to interpret or judge them, is said to lead to a gradual lessening of one's identification with those thoughts. Negative self-referential thoughts are progressively seen as mere temporary mental events, and therefore not as negative self-defining reifications. A second proposed positive effect is an enhanced sense of equanimity (Desbordes et al., 2015), a non-judgmental metacognitive awareness of the broad spectrum of sensations and thoughts that may arise at any given point in time. In the context of YBP, we propose that this process is first primarily applied to bodily sensations and proprioceptive feedback related to the movement and breath, and subsequently also to arising emotions and thoughts. Preliminary support for this view comes from the finding that yoga practitioners seem to exhibit increased pain tolerance, putatively mediated by acquired tendencies to simply attend to the sensation, observe the pain without reacting, and accept the associated experience (Villemure et al., 2014). On a similar note, yoga practitioners were found to exhibit less top-down cognitive control when viewing emotional stimuli, suggesting less engagement in active attempts to cognitively restructure the affective experience (Froeliger et al., 2012b).

Use of the Gaze as a Tool for Training Attentional Focus

Some YBP use gaze as a tool for training attention and inducing a calm state of mind (Hedstrom, 1991). A few texts of YBP describe details of "eye exercises" (Satchidananda, 1970) including gazing techniques in which the eyes are held in a particular position (e.g., upward, inward or downward). These exercises are recommended to "aid powers of concentration" (Schwendimann, 1961), and prevent one's attention from being distracted (Bahm, 1965). YBP often involve explicit instructions to avoid eye movements to potentially distracting stimuli in the visual environment, and to instead cultivate a controlled gaze towards specific body parts. There is typically an emphasis on performing eye movements consciously and slowly, and on coordinating them with the breath as well as specific physical postures. Lastly, it has been proposed that gaze directed within the upper visual field promotes more allocentric referential processing relative to gaze directed within the lower visual field (Sdoia et al., 2004). Since YBP employ both, they may promote the dynamic integration of allocentric and egocentric reference frames, which may in turn facilitate the ability to monitor the visual environment with less personal bias (Austin, 2009).

Neurocircuitry and Physiological Processes Hypothesized to be Implicated in Yoga-based Practices

Having deconstructed the components of movement, breath and attention, we will now outline the main implied neurocircuitry and physiological processes (**Figure 2**). Our aim is to inform specific hypotheses regarding the mechanisms of change affected by YBP.

Neurocircuitry Implicated in Movement-Related Aspects of YBP

Many of the movement-related aspects of YBP engage basal ganglia (BG) and cerebellar circuits. The BG comprise a group of subcortical gray matter nuclei located at the base of the forebrain, including the striatum (putamen, caudate nucleus and nucleus accumbens), the globus pallidus, the subthalamic nucleus, and the substantia nigra (Martin, 2003). The BG are connected to the cortex and the cerebellum via a series of semi-independent loops (McHaffie et al., 2005). Each of these loops originates from a specific cortical region, passes through functionally corresponding portions of the BG, and returns to the same cortical area via the thalamus (Alexander, 1994).

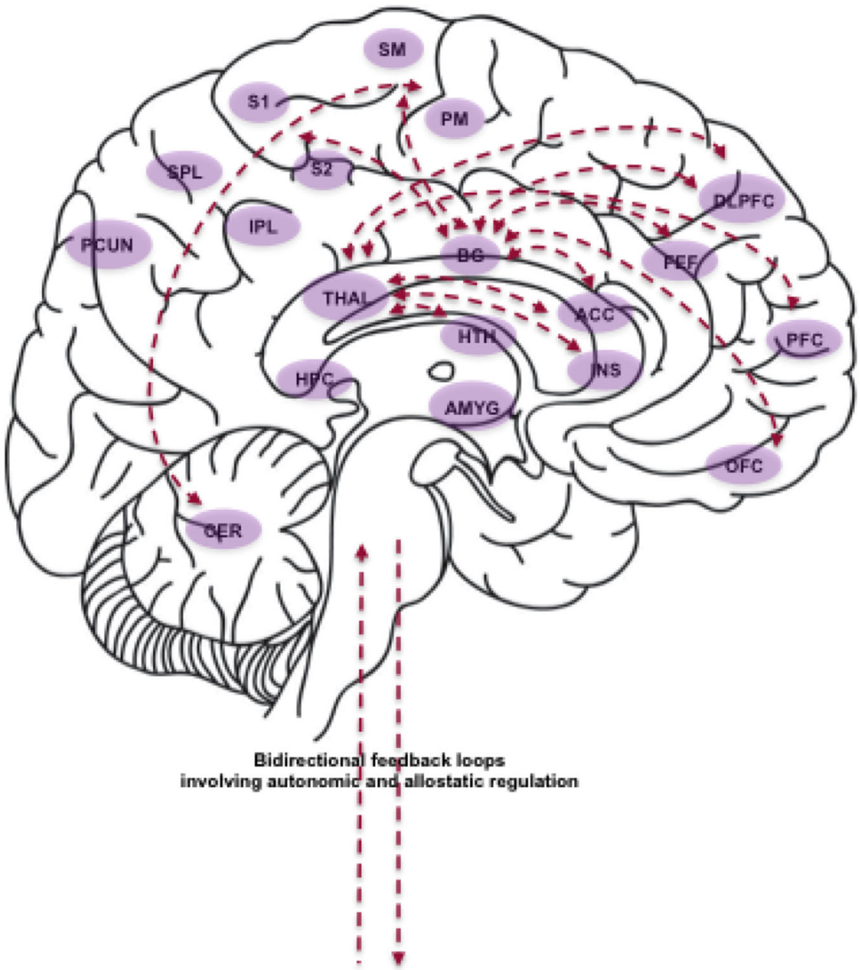

FIGURE 2 | Schematic depiction of some of the brain areas, neural circuits and physiological processes proposed to be affected by YBP. Abbreviations (in alphabetical order): ACC (Anterior Cingulate Cortex); AMYG (Amygdala); BG (Basal Ganglia); CER (Cerebellum); DLPFC (Dorsolateral Prefrontal Cortex); FEF (Frontal Eye Fields); HPC (Hippocampus); HTH (Hypothalamus); INS (Insula); IPL (Inferior Parietal Lobule); OFC (Orbitofrontal Cortex); PCUN (Precuneus); PFC (Prefrontal Cortex); PM (Premotor Cortex); S1 (Primary Somatosensory Cortex); S2 (Secondary Somatosensory Cortex); SM (Supplementary Motor Cortex); SPL (Superior Parietal Lobule); THAL (Thalamus). **The role of BG and cerebellar circuits**: BG circuits involving PM and SM support the coordination of complex movements. BG circuits involving the DLPFC, OFC and ACC support executive functioning and procedural learning implicated in the planning and learning of motor sequences. BG circuits involving the DLPFC additionally support working memory required for the execution of motor sequences. BG circuits involving S1, S2, DLPFC, and ACC support somatosensory processing as well as the perception of noxious stimuli. BG circuits involving FEF support voluntary eye movements and gaze control. Lastly, CER circuits involving PM and SM support motor coordination and action execution. **Brain areas and neural circuits supporting body-focused attention and interoceptive awareness**: The INS is the key neural structure for the processing of both exteroceptive (somatic) and interoceptive (physiological) information for bodily awareness and autonomic regulation. The ACC supports the processing of noxious stimuli as well as error detection and conflict monitoring. S1 and S2 are the core regions for the processing of tactile and proprioceptive sensations. The PCUN supports higher-order body awareness, self-related processing and attentional shifting. The IPL and SPL are involved in the computation of body size and shape, and in the integration of multimodal spatial information in body-centered coordinates. The PFC supports executive control and self-referential processing. **Integration of bottom-up and top-down processes**: The breath employed in YBP putatively promotes synchronization of cortical areas via stimulation of THAL nuclei, with a consequent positive impact on alertness and executive functioning. In addition, slow and rhythmic breathing is known to promote vagal tone and in turn reduce allostatic load. The THAL mediates vagal afferent information to the INS, ACC and PFC, which are all involved in self-regulatory processes. The AMYG supports fear-detection, and consequent modulation of autonomic states. The HPC contains stress hormone receptors that can influence the evaluation and memory of stress-related events.

The major input nuclei of the BG are the putamen and caudate nucleus, which receive afferent information from the cortex (cortico-striatal projections) as well as the intralaminar nucleus of the thalamus (thalamo-striatal projections). The majority of top-down cortico-striatal projections come from five regions of the frontal lobes—the premotor and supplementary motor areas, the frontal and supplemental eye fields, the orbital frontal cortex, the dorsolateral prefrontal cortex, and the anterior cingulate. The major output nuclei of the BG are the globus pallidus and the pars reticulate of the substantia nigra, which project in turn to the thalamus and back to the cortex—primarily to premotor and motor cortices as well as to prefrontal areas (Arsalidou et al., 2013).

As mentioned earlier, YBP involve the execution of postures and movement sequences that require a high degree of coordination. The BG support this type of bodily movement via loops with cortico-striatal projections from premotor and supplementary motor areas (Arsalidou et al., 2013). These loops are part of the extrapyramidal motor system, which is responsible for the modulation of neural impulses that originate in the cerebral cortex. Such modulations are involved in the initiation and selective activation of certain movements while suppressing others, setting the rate and force of movements, and coordinating movements. Hence, a central function of these loops, which operate in conjunction with parallel loops involving the cerebellum, is the selection and triggering of well-coordinated voluntary movements (DeLong and Georgopoulos, 2011).

Movement in the context of YBP also involves executive functioning and procedural learning, which are implicated in the planning and learning of motor sequences as well as in decision making according to neuromuscular feedback in the context of postural adjustments. The BG support executive functioning via loops with cortico-striatal projections from the dorsolateral prefrontal cortex, the orbitofrontal cortex, and the anterior cingulate cortex (ACC; Arsalidou et al., 2013). Such executive processes include planning, problem solving, set-shifting and decision making, which are all crucial for procedural learning (Monchi et al., 2006). BG involvement in procedural learning has in fact been shown across several modalities (including kinesthetic/vestibular, visual, olfactory, and auditory), and been found to generalize across mammalian species (Packard, 2009).

The execution of postures and movement sequences in YBP also relies on working memory, as it requires the ability to hold in mind instructions and consequently select very specific sequential motor actions. The BG support working memory via loops with cortico-striatal projections from the dorsolateral prefrontal cortex (Arsalidou et al., 2013). In humans, these loops BG seem to be particularly involved in motor habit learning (DeLong and Georgopoulos, 2011). An important function of working memory in this context is to predict a forthcoming event so that the motor system can prepare for action. That is, based on information stored in working memory, and through mechanisms of inhibition and dis-inhibition, the BG are responsible for "opening the gate" for specific motor actions in a predictive manner (Hikosaka et al., 2000).

The fact that a large majority of the initial studies investigating the functional role of the BG were based on patients with motor dysfunction such as Parkinson's Disease (Chenery et al., 2008) or Huntington's Disease (Paulsen, 2009), led to the traditional view that the BG are primarily associated with motor functions. However, subsequent studies have shown that the BG are also implicated in cognitive disorders such as attention deficit hyperactivity disorder (ADHD; Knutson and Gibbs, 2007) and obsessive compulsive disorder (OCD; Huyser et al., 2009). Moreover, converging evidence from studies in healthy populations suggests that BG are involved in a series of more complex functions including somatosensation, higher order cognitive functions, and even social behavior (Arsalidou et al., 2013), all of which seem to rely on at least partially differential cortico-BG feedback loops. The same is true for the cerebellum, which has long been known for its involvement in motor coordination, but more recently also recognized for its involvement in cognitive functioning and emotional processing (Schmahmann and Sherman, 1998; Strata et al., 2011; Baumann and Mattingley, 2012). Action execution and task performance are primarily supported by motor-cerebellar circuits, whereas cognitive functioning and emotional processing are primarily supported by prefrontal-parietal-cerebellar circuits (Balsters et al., 2014). We hypothesize that YBP may promote increased connectivity within, and dynamic shifting between, motor, cognitive and emotional neurocircuitry of both the BG and the cerebellum, with potential beneficial effects for mind-body integration and self-regulation. Supporting evidence for this hypothesis comes from a recent neuroimaging study documenting more widespread functional connectivity within BG cortico-thalamic feedback loops in yoga and meditation practitioners compared to controls (Gard et al., 2015).

Physiological Effects of the Breath Employed in YBP

It has been shown that slowing down the breathing rate to about six breaths per minute with matched inhalations and exhalations decreases chemoreflex sensitivity—i.e., the naturally occurring change in breathing rate in response to changes in the concentration of oxygen and carbon dioxide in the blood (Spicuzza et al., 2000). Application of this specific breathing rhythm also decreases oxidative stress—i.e., an imbalance between the production of reactive oxygen species and antioxidant defenses (Sharma et al., 2003). In addition, paced breathing increases the release of prolactin and oxytocin release which can promote feelings of calmness and social bonding (Torner et al., 2002).

The previously described ujjayi breath involves contraction of laryngeal muscles, which creates an increase of airway resistance hypothesized to stimulate somatosensory vagal afferents to the brain (Brown and Gerbarg, 2005a), and in turn promote improved autonomic regulation (Calabrese et al., 2000). Furthermore, breath employed in YBP may promote synchronization of cortical areas via stimulation of thalamic nuclei, with a consequent positive impact on alertness and executive functioning (Calabrese et al., 2000; Tsigos and Chrousos, 2002).

Lastly, it has been shown that fluctuations of depth and rate of breathing during fMRI scanning correlate with blood-oxygen-level dependent (BOLD) signal changes in regions with high blood volume (Birn et al., 2006). Interestingly, these changes have been found to largely overlap with the so-called default mode network (DMN) consisting of brain regions that are active during wakeful rest (Raichle et al., 2001). Other regions showing the strongest breath-related signal changes include the cerebellum, BG (putamen and caudate nucleus), insula, ACC, orbitofrontal cortex, dorsolateral and ventrolateral prefrontal cortex, and the supplementary motor area (Chang and Glover, 2009).

Neural Correlates of Attention Regulation in YBP

Body-Focused Attention and Interoceptive Awareness

Most of what we know to date about the neural correlates of body-focused attention in contemplative practices is based on studies of body-centered meditation and mindfulness-based techniques with a limited active movement component. According to a recent meta-analysis (Fox et al., 2014), gray matter regions that have been found to undergo structural changes associated with meditation practice include the insular cortex, primary and secondary sensorimotor cortices, and the anterior precuneus. The insula is a key neural substrate for interoceptive awareness (Critchley, 2005; Craig, 2009). Information about interoceptive signals is first transmitted via the brainstem and the thalamus first to the posterior insula, which is the primary interoceptive cortex. Subsequently, it is transmitted to the anterior insula, where the information is integrated with other contextual information that make it accessible to consciousness (Damasio and Carvalho, 2013). Primary and secondary somatosensory cortices represent the main locus for the processing of tactile and proprioceptive sensations (Venkatesan et al., 2014). The precuneus in contrast has been suggested to play an important role for higher-order body awareness as well as more generally for self-related processing and attentional shifting (Cavanna and Trimble, 2006). In terms of white matter pathways relevant to body-focused attention, structural changes have been reported in the superior longitudinal fasciculus (Fox et al., 2014). It consists of rostro-caudal fiber pathways that connect dorsal temporo-parietal regions with prefrontal regions (Makris et al., 2005). Hence, it can be assumed to play an important role in connecting parietal body awareness regions and prefrontal executive regions.

A meta-analysis of functional brain changes associated with meditation practices (Tomasino et al., 2013), also revealed changes in a number of areas involved in the processing of bodily signals, likely reflecting the body-focused attention applied in these practices. Specifically, consistent changes in activation have been reported in parietal areas involved in spatial and somatosensory processing (the superior and inferior parietal lobule), the right supramarginal gyrus, and again the insular cortex. The superior parietal lobule is involved in integrating multimodal spatial information in body-centered coordinates (Felician et al., 2004). The inferior parietal lobule is involved in the computation of the size and shape of the body and body parts (Ehrsson et al., 2005). The supramarginal gyrus has been found to be activated during disembodiment and altered integration of multisensory information (Blanke and Mohr, 2005). And lastly, as mentioned previously, the insular cortex is known for its role in processing both exteroceptive (somatic) and interoceptive (physiological) information that is crucial for bodily awareness and autonomic regulation (Critchley, 2005).

There is preliminary evidence that YBP may also be associated with structural changes in brain areas involved the processing of bodily sensations. In fact, Villemure and colleagues (Villemure et al., 2014) found that yoga practitioners had increased GMV in the insula, cingulate cortex, medial prefrontal cortex, and inferior and superior parietal lobule, as well as increased intra-insular white matter connectivity. Similarly, Froeliger and colleagues (Froeliger et al., 2012a) also found increased GMV in the insula and cerebellar regions of yoga practitioners compared to controls. While these findings are certainly of interest, it is important to keep in mind that it is not yet known to which extent they reflect changes driven by aspects specific to YBP, as opposed to changes driven by more general aspects of bodily attention also employed in mindfulness-based techniques. Studies directly comparing movement-based yoga-practices and standard mindfulness-based practices will be crucial for addressing this point.

Further expanding on the neural correlates of increased body awareness, Kerr and colleagues (Kerr et al., 2013) outlined a theoretical framework proposing that body-focused attention elicits changes in brain dynamics that enhance signal-to-noise ratio in attentional processing across different modalities. Specifically, they propose that somatically focused practice enhances attentional control of the 7–14 Hz alpha rhythm, which is said to be crucial for regulating input and signal-to-noise ratio not only for sensory cortices but across the neocortex (Kerr et al., 2011). The concrete and tangible nature of somatic information and feedback is thought to represent an efficient "tool" for learning how to modulate the alpha rhythm, so that with sustained practice the flow of information is then more efficiently filtered and prioritized throughout the brain. The view that localized somatosensory alpha modulation training can lead to a more general increase of attentional control, is consistent with studies on body-focused mindfulness practices showing long-term changes in prefrontal cortex activation (Davidson et al., 2003; Farb et al., 2012), or enhanced performance in tests of visual selective attention (Jha et al., 2007; Jensen et al., 2012). In addition, the sensory alpha modulation framework is corroborated by the proposal that the transition from FA to a more OM type of attention by experienced meditation practitioners, may be partly promoted because of improved control over alpha rhythm phase dynamics (Mathewson et al., 2011). The extent to which these findings of functional brain changes and the consequent general attentional enhancement associated with mindfulness-based practices will also be found in YBP, remains a fundamental question to be addressed by future research studies.

Lastly, we would like to briefly address the role of the BG in body awareness. The BG are involved in somatosensory processing and the perception of noxious stimuli via loops with cortico-striatal projections from somatosensory areas, the dorsolateral prefrontal cortex and ACC (Arsalidou et al., 2013). Many BG neurons are responsive to somatosensory stimulation, and particularly to nociceptive stimulation. In fact, evidence from neurophysiological, clinical and behavior experiments suggests that the BG are uniquely involved in the complex function of integrating motor, emotional, autonomic and cognitive responses to pain (Borsook et al., 2010). Such processing is particularly relevant for YBP, which often involve challenging physical and emotional sensations.

Mind-Wandering and Metacognition

In the previous section of our paper we proposed the view that YBP may primarily employ an OM type of attention, with a constant interplay of MW and metacognitive awareness. MW is said to predominantly engage regions of the DMN (Raichle et al., 2001), with self-referential spontaneous thoughts being reflected by activation of the posterior cingulate cortex (PCC) and the anterior medial prefrontal cortex in particular (Andrews-Hanna, 2012). Metacognition, on the other hand, is said to predominantly engage higher order prefrontal regions (Fleming and Dolan, 2012) including the anterior and dorsolateral prefrontal cortices, as well as the ACC and the anterior insula, which is proposed to subserve meta-awareness of internal bodily states (Critchley, 2005).

Neuroimaging studies of mindfulness-based practices have provided evidence for alteration of both DMN (Ives-Deliperi et al., 2011) and metacognitive (Manna et al., 2010) brain regions, indicating that contemplative practitioners may indeed consistently engage both. We speculate that the same is true for YBP. As mentioned earlier, the practice of non-judgmental metacognitive monitoring of sensations and spontaneous thought processes is likely to promote increased emotional awareness, non-reactivity and equanimity. Cultivating emotional awareness implies involvement of brain circuitry implicated in emotional regulation such as the limbic system, the ACC and prefrontal regions (Farb et al., 2012). In addition, the BG support emotion processing via loops with cortico-striatal projections from the dorsolateral prefrontal cortex and ACC (Arsalidou et al., 2013).

Gaze Training

Studies investigating the relationship between gaze and self-regulation of alpha waves in the brain, provide relevant information about the neural processes that are affected when gaze is used to train attention. It is known that the presence of alpha rhythm in occipital/visual brain regions is associated with a state of relaxed wakefulness (Haegens et al., 2014). While alpha waves typically occur with closed eyes, individuals can be trained to induce alpha waves with eyes open as long as the attention is "turned inward" (Green et al., 1979). It is suggested that alpha production in this case is related to a defocus and relaxation of ocular convergence, a technique that is very similar to a yogic eye posture known as "bhrumadhya dhrishti" (Bahm, 1965).

Controlled gaze towards specific body parts, and concomitant avoidance of eye movements towards distracting stimuli, has also been associated with specific neural correlates. fMRI data indicate that inhibiting saccades and redirecting gaze toward a target engages a frontal oculomotor network including the medial frontal cortex, frontal and supplementary eye fields, and the striatum, known to be involved in action inhibition and performance monitoring (Thakkar et al., 2014). Furthermore, evidence from ERP studies suggests that gazing at a body part enhances tactile acuity (Forster and Eimer, 2005), spatial attention, (Gherri and Forster, 2014), and more generally activation of fronto-parietal networks representing peripersonal space (Gillmeister and Forster, 2010).

Finally, important neural structures for gaze control are the BG. Specifically, the BG are involved in voluntary eye movements via loops with cortico-striatal projections from frontal and supplemental eye fields via the superior culliculus (Arsalidou et al., 2013). These loops are implicated in controlling saccadic eye movements, in particular in preventing distracting visual input from triggering unwanted saccadic eye movements, as well as smooth pursuit (Hikosaka et al., 2000). Given that spatial orienting through eye movements is known to be associated with the orienting of attention (Schneider and Deubel, 2002), this function of the BG is likely to play an important role in fostering the attentional control applied in YBP.

Hypothesized Effects of Yoga-based Practices on the Regulation of Allostatic Load and the Integration of Bottom-up and Top-down Processes

We will now address two further possible aspects that may underlie the mechanisms of change promoted by YBP, namely the regulation of allostatic load and the integration of bottom-up and top-down processes (**Figure 2**).

Regulation of Allostatic Load

The concept of allostasis refers to the ability of an organism to maintain stability/homeostasis through change by actively adjusting to both predictable and unpredictable events (McEwen and Wingfield, 2003). In humans, primary mediators of allostasis include, but are not restricted to, hormones of the hypothalamo–pituitary–adrenal (HPA) axis (e.g., cortisol), excitatory catecholamines (e.g., adrenaline), and immunomodulatory cytokines (e.g., interleukins). An imbalance of these primary mediators results in allostatic state, and cumulative effects of sustained allostatic state over time in turn results in allostatic load (Juster et al., 2010). It is important to note that while most primary mediators of allostatic load can have protective effects in the short run, the physiological integrity of the organism is compromised if the allostatic load is sustained over time (McEwen, 1998).

One of the key components for the regulation of allostatic load in humans is the vagus nerve, the 10th of the cranial nerves. Its axons emerge from and converge onto four different brainstem nuclei, and it regulates several visceral organs, as well as striated muscles of the face, head and neck (Porges, 1995). The majority (80–90%) of the vagal nerve fibers are afferent, thus communicating peripheral information about bodily states to the brain (Berthoud and Neuhuber, 2000). The function of the vagus nerve has evolved phylogenetically, and in mammals the vagus system is primarily involved in mediating stress responses by regulating CO and influencing engagement/disengagement with the environment (Porges, 2001). In fact, physical, affective as well as cognitive and social processes have all been shown to be associated with vagally mediated cardiac function (Porges, 2007). It has been proposed that vagal tone can be assessed by measuring the variability of the inter-beat intervals of the heart, i.e., HRV (Porges, 2001), and that vagal tone is especially mirrored by the HRV within the frequency of normal respiration rate, i.e., respiratory sinus arrhythmia (RSA; Calabrese et al., 2000). Furthermore, it as been hypothesized that there is an interaction between breathing frequency and HRV as well as arterial baroreflex sensitivity, with slower breathing rates promoting an increase of both these indices (Bernardi et al., 2001). However, the complex interplay between heart rate and vagal sensory input call for more careful analyses (Berntson et al., 2007).

We speculate that YBP are intrinsically tailored to promote vagal tone and facilitate a decrease of allostatic load in several ways. First, there is the direct parasympathetic effect of slow and rhythmic breathing with increased airway resistance known to increase HRV (Brown and Gerbarg, 2005a). Second, many of the postures employed in YBP enhance the depth of the breath (e.g., active expansions/contractions of the rib cage during back/forward bends), strengthening core diaphragmatic muscles and enhancing baroreceptor sensitivity (Strongoli et al., 2010). Third, most postures emphasize abdominal tone through the application of interior muscle activation, which additionally promotes peripheral vagal stimulation and afference (Ritter et al., 1992). Lastly, on a more indirect level, the practice of maintaining a calm breathing rhythm during the physical, mental an emotional challenges of the postures and movement sequences, represents an opportunity to apply non-reactive awareness and cultivate a state of equilibrium in the face of stress. Hence, YBP represent an effective way of developing strategies for dealing with stressful experiences while cultivating an internal sense of calmness. The ultimate goal, of course, is to generalize these skills from the practice on the mat to everyday life situations. In sum, YBP offer a combination of tools for decreasing allostatic load via vagal afference, with a consequent increase of parasympathetic activation and promotion of self-regulatory mechanisms.

Integration of Bottom-up and Top-down Processes

From the previous sections it is evident that YBP involve a rich and complex set of both bottom-up physiological and top-down cognitive processes, and there are various ways in which these processes interact and influence each other. Proponents of theoretical frameworks such as allostatic regulation (McEwen and Wingfield, 2003) and the polyvagal perspective (Porges, 2007), emphasize the strong link between visceral regulation and the functioning of the central nervous system, and advocate that there is no real functional separation between the viscera and the brain. Many of the studies of bottom-up/top-down interactions involve risk evaluation and emotional processing, and they outline both bottom-up influences on higher brain functions, and top-down regulation of physiological processes. Crucial structures for the bidirectional signaling between the body and the brain involve the hippocampus and the amygdala, as they process experiences by interfacing with both brainstem areas involved in metabolic regulation, and prefrontal areas involved in attentional control (McEwen and Gianaros, 2011).

The concept of neuroception (Porges, 2003) refers to the contribution of bottom-up processes such as vagal afference, sensory input, and endocrine mechanisms to the detection and evaluation of environmental risk prior to the conscious elaboration by higher brain centers. Vagal afferent information is mediated via the thalamus to the insula, anterior cingulate and prefrontal cortex, which are all involved in emotion regulation (Thayer and Sternberg, 2006). Similarly, it has been shown that afferent input from the heart influences the activity of brain regions involved in emotional, perceptual and attentional processing, and that individual differences in HRV can predict attentional inhibition (Park et al., 2012). Moreover, the secretion of stress hormones can influence the evaluation and memory of threat related events via hormone receptors in the hippocampal formation (McEwen, 2013). Conversely, by detecting and evaluating risk, higher order brain centers modulate autonomic states and the expression of adaptive defensive behaviors. For example, structures such as the amygdala and prefrontal cortex, which are involved in fear-detection, attentional mechanisms, executive function and self-regulatory behaviors (McEwen and Gianaros, 2011), are linked via the vagus nerve to the regulation of metabolic systems (Thayer and Sternberg, 2006). Similarly, temporal regions involved in the perception of biological movement, faces and vocalizations (Adolphs, 2002), can trigger or inhibit physiological responses and affect allostatic load (Porges, 2007). As a result of the bidirectional neurocircuitry involved in stress regulation, the brain can also undergo structural changes over time. In fact, it has been shown that even in otherwise healthy individuals, chronic exposure to stress can alter GMV in the hippocampus, amygdala and prefrontal cortex (Ganzel et al., 2008).

Given that YBP employ both bottom-up and top-down mechanisms, they lend themselves as a method for dynamically exploring the interplay between the body's stress responses and regulatory systems (Streeter et al., 2012). Physiological stress responses may be elicited by the physical, emotional or mental challenges that arise during the practice. As these occur, both bottom-up breath-related and top-down attention-related processes are constantly employed to counteract them and reinstall a balance within the system. The movement, in turn, allows for these processes to be applied in a dynamic and ecological way, that consequently makes the effects of YBP likely more generalized to everyday life situations.

Conclusion

In this paper we propose a definition of YBP with the aim of providing a comprehensive theoretical framework applicable within Western science, from which testable scientific hypotheses can be formulated.

We begin by presenting a brief overview of the extant literature investigating the effects of YBP in healthy populations, with a specific focus on physiological parameters, body awareness, self-reported emotional states and stress, and cognitive functioning. We then discuss some of the methodological shortcomings of previous studies, with particular emphasis on the inappropriate selection of experimental populations and control groups, the use of self-report outcome measures, poorly described interventions, mostly neglected investigations of individual component parts of the programs, and the lack of hypotheses about specific neurophysiological and neurocognitive mechanisms underlying the reported effects of YBP. Subsequently, we outline the main component parts of YBP, which commonly consist of a combination of postures or movement sequences, conscious regulation of the breath, and various techniques to improve attentional focus. We believe that a detailed deconstruction of these component parts is essential for their operationalization and for a better understanding of their respective effects. Lastly, we discuss some of the main neurophysiological and neurocognitive processes hypothesized to underlie the mechanisms of change promoted by YBP. We propose that compared to mindfulness-based practices, the rich set of movement, breath and attention components employed in YBP may more directly engage the vagal afferent system as well as BG and cerebellar circuits, with consequent possibly enhanced effects on autonomic, emotional and cognitive regulation.

In sum, we believe in the importance and potential of future research investigating the mechanisms underlying YBP, so that they may be more effectively adapted and applied in various clinical, educational and recreational settings. The theoretical framework presented in our paper is by no means exhaustive, but only intending to represent a starting point from which specific hypotheses for future research can be formulated. We hope that it will inspire further work in the field with the ultimate aim of unveiling the full potential of YBP in modern contexts.

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The development of an RDoC-based treatment program for adolescent depression: "Training for Awareness, Resilience, and Action" (TARA)

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Major depressive disorder (MDD) is one of the current leading causes of disability worldwide. Adolescence is a vulnerable period for the onset of depression, with MDD affecting 8–20% of all youth. Traditional treatment methods have not been sufficiently effective to slow the increasing prevalence of adolescent depression. We therefore propose a new model for the treatment of adolescent depression – *Training for Awareness, Resilience, and Action (TARA)* – that is based on current understanding of developmental and depression neurobiology. The TARA model is aligned with the Research Domain Criteria (RDoC) of the National Institute of Mental Health. In this article, we first address the relevance of RDoC to adolescent depression. Second, we identify the major RDoC domains of function involved in adolescent depression and organize them in a way that gives priority to domains thought to be driving the psychopathology. Third, we select therapeutic training strategies for TARA based on current scientific evidence of efficacy for the prioritized domains of function in a manner that maximizes time, resources, and feasibility. The TARA model takes into consideration the developmental limitation in top-down cognitive control in adolescence and promotes bottom-up strategies such as vagal afference to decrease limbic hyperactivation and its secondary effects. The program has been informed by mindfulness-based therapy and yoga, as well as modern psychotherapeutic techniques. The treatment program is semi-manualized, progressive, and applied in a module-based approach designed for a group setting that is to be conducted one session per week for 12 weeks. We hope that this work may form the basis for a novel and more effective treatment strategy for adolescent depression, as well as broaden the discussion on how to address this challenge.

Keywords: adolescent depression, RDoC, treatment development, emotion regulation, attention training, yoga-based movement, mindfulness

INTRODUCTION

The World Health Organization (WHO) identifies major depressive disorder (MDD) as one of the current leading causes of disability worldwide (Ferrari et al., 2013). Adolescence is a vulnerable period for the onset of depression, with MDD affecting 8–20% of all youth (Kessler et al., 2007; Thapar et al., 2012). MDD is often recurrent and early onset MDD predicts a four-fold increase in the risk of developing adult depression (Naicker et al., 2013). Depressed adolescents are at higher risk of future psychiatric morbidity including substance use disorder, cognitive impairment, and increased risk of suicide (Birmaher et al., 2002). Approximately 13–20% of the children living in the United States experience a psychiatric disorder often including depressive disorders, with suicide being the second leading cause of death among US children aged 12–17 years in 2010 (Perou et al., 2013). During 1994–2011, the prevalence of psychiatric conditions increased, and is now estimated to cost the U.S. $247 billion annually (Perou et al., 2013). Thus, early detection and effective treatment methods would relieve the burden imposed by MDD on the afflicted individual and society as a whole.

Traditional treatment methods for adolescent depression such as anti-depressive medication and psychological cognitive strategies such as cognitive behavioral therapy (CBT) have not been sufficiently effective to slow the increasing prevalence of this disorder. Follow-up studies of both pharmacotherapy and psychotherapy randomized controlled trials (RCTs) show that 25–50% of the depressed adolescents relapse within 6 months to 2 years post-treatment (March and Vitiello, 2009). A recent Cochrane meta-analysis concluded that there is very limited evidence demonstrating the relative effectiveness of antidepressant medication, psychological interventions, and a combination of these interventions in depressed youth (Cox et al., 2012). However, despite the fact that pharmacological treatments of mild to moderate adolescent MDD have not shown significant treatment effects and may introduce both short- and potential long-term negative side effects (Hetrick et al., 2007; Adegbite-Adeniyi et al., 2012), 14.1% of adolescents with primary mood disorders are treated with antidepressant medication in the U.S. (Merikangas et al., 2013).

Thus far, the quest for biomarkers that may better characterize specific subtypes of depression or aid in the personalization of depression treatment has not yet improved treatment efficacy for adolescent depression. Furthermore, the advances in scientific understanding of neuroplasticity and neurodevelopment have not been translated into clinical applications or, have yielded established treatment models of adolescent depression. We therefore propose a new model for the treatment of adolescent depression – *Training for Awareness, Resilience, and Action (TARA)* – that is based on our current understanding of developmental and depression neurobiology. In designing the TARA program, we have carefully considered the key elements of neural plasticity that were highlighted in the National Institute of Health Blueprint for Neuroscience Research Workshop for creating successful clinical interventions: time-sensitivity and the creation of a platform for attention and behavioral motivation (Cramer et al., 2011). The TARA program for adolescent depression is time sensitive since we intervene during peak brain plasticity. We propose to use breathing exercises, yoga-based movement and short meditation practices to create the foundation for improved attention. The motivation for behavioral change in the TARA program is linked to subjective experience and guided by the participant's own core values. The intervention is designed in a progressive and module-based manner so that the mechanisms that drive the psychopathology are first addressed.

In this paper, we first introduce the Research Domain Criteria (RDoC) and its relevance to the research field of adolescent depression. We then describe the domains of function central to the psychopathology of adolescent depression and organize these domains of function hierarchically, prioritizing the domains of function that are thought to be driving the psychopathology. Next, we selected therapeutic and training strategies based on their feasibility and the current scientific evidence to target these domains of function. We outline our selection process in a pragmatic way to fit our neurodevelopmental, neurobiological, and metabolic theory of change. Finally, we present a structured, progressive, and individually adaptable module-based program in which the first step consists of techniques targeting the domain of function highest in the hierarchy.

ALIGNMENT WITH THE NATIONAL INSTITUTE OF MENTAL HEALTH'S RESEARCH DOMAIN CRITERIA

The National Institute of Mental Health's (NIMH) RDoC Project, as described by Insel et al. (2010) intends to "develop a research program which incorporates data on pathophysiology in ways that eventually will help identify new targets for treatment development, detect subgroups for treatment selection, and provide a better match between research findings and clinical decision making" (Insel et al., 2010). It is based on the assumption that mental illnesses are related to dysfunction of relevant brain circuits, which can be identified by clinical neuroscience. The levels of analysis progress from measures of circuitry function upward to clinical manifestations or downward to the genetic and molecular/cellular factors influencing these functions. The RDoC project identifies five broad domains of function, which may contribute to psychopathology in varying degrees across a range of clinically defined psychiatric disorders (Insel et al., 2010): negative valence, positive valence, cognition, social processes and arousal/modulation. The structure of the RDoC is described as "a matrix in which the rows represent various constructs grouped hierarchically into broad domains of function. The columns of the matrix denote different levels of analysis, from genetic, molecular, and cellular levels, proceeding to the circuit-level to the level of the individual, family environment, and social context" (Insel et al., 2010). For a graphic illustration of the RDoC matrix, see (http://www.nimh.nih.gov/research-priorities/rdoc/nimh-research-domain-criteria-rdoc.shtml#toc_matrix).

The application of the RDoC approach instead of the Diagnostic and Statistical Manual of Mental Disorders (DSM) system is especially relevant in the research field of adolescent depression. The DSM diagnostic criteria for adolescent MDD have low diagnostic validity and specificity, with unclear diagnostic boundaries (Costello et al., 2003; Ford et al., 2003; Korczak and Goldstein, 2009; Alexandrino-Silva et al., 2012; Henje Blom et al., 2014; Schuch et al., 2014). Psychiatric comorbidity is also highly prevalent in adolescent depression (Angold and Costello, 1993; Middeldorp et al., 2005; Spencer, 2006; Hettema, 2008). These factors contribute to heterogeneous sample configurations when recruiting depressed adolescents for research on the basis of DSM criteria and makes it very hard to tailor an effective treatment for the heterogeneous population that the DSM MDD diagnosis will encompass. Consequently, from a neuroscientific research perspective it may be more relevant to study the different brain circuits implicated in adolescent depression, such as those important to emotion regulation, attention, motivation, stress responses, social cognition, reward processing, and neuro-vegetative functions in patients who may potentially span multiple DSM diagnoses (Joormann and Goodman, 2014). Ultimately, brain development should also be taken into account in the RDoC constructs since the implicated brain circuits mature within different time frames and thus give rise to age-dependent symptomatology (Drevets et al., 2008). The neurocircuitry implied in adolescent depression often overlaps between different domains and constructs. Therefore, to maximize time, resources, and feasibility in designing an intervention model for adolescent depression, we suggest specific neural circuits to be targeted in our treatment model rather than all of the neurocircuitry described in each construct. While a RDoC based approach to develop a treatment program for geriatric depression has previously been developed and applied (Alexopoulos and Arean, 2014), our approach to use the RDoC in combination with developmental aspects of the brain as the foundation for creating a treatment model for adolescent depression is the first of its kind.

The transition from the DSM system to RDoC is a challenge in our research design, since on the one hand we have adolescent depression as a starting point, which is a diagnostic entity (i.e., MDD) that is constituted of symptoms that may arise from different RDoC constructs and originate in different neural pathways, and on the other hand we try to tease out distinct neurocircuitry that have a behavior or symptom-related feature which is possible to identify across different DSM diagnostic entities. Our solution to this challenge is a pragmatic one: to base our hypothesis on the most common clinical manifestations of adolescent depression, which is not congruent with the MDD DSM categories and which extend beyond one specified RDoC construct. Consequently, both unspecific and specific symptoms according to the DSM will be addressed.

In summary, the RDoC approach gives us an opportunity to address specific dimensions of psychopathology in a hierarchical manner according to what we hypothesize drives the pathophysiology of adolescent depression. For instance, giving priority to target anxious arousal, worrying and rumination specifically, allows us to assess these dimensions from a neuroscience perspective. We aim to find out whether this approach will aid the development of a more targeted and efficient treatment for adolescent depressive symptoms.

BRAIN DEVELOPMENT AND VULNERABILITY TO DEPRESSION

During childhood, the brain undergoes an overproduction of synapses and gray matter. Throughout normal brain development, excess neural connections are then progressively pruned (Giorgio et al., 2010). Subcortical areas, such as the brainstem and limbic structures involved in basic functions and emotional processing mature earlier in life (Gogtay et al., 2004). Higher order cortical regions, specifically the prefrontal and frontal cortices responsible for executive functioning and cognitive control are not fully developed until the mid-20's (Giorgio et al., 2010; Fjell et al., 2012). Thus, the adolescent brain differs from the adult brain in frontal development and frontolimbic connections (Gogtay et al., 2004). It has been suggested that altered development of these neural circuits increases the risk for depression (Andersen and Teicher, 2008; Pandey et al., 2013). The differing rates between subcortical and cortical maturation during adolescence may increase vulnerability to emotional reactivity, as the absence of effective top-down regulation from prefrontal and frontal regions on limbic reactivity may be a possible contributing mechanism to developing depressive symptoms (Cunningham et al., 2002; Gogtay et al., 2004; Yurgelun-Todd and Killgore, 2006). This neural pattern of development that subserves limited top-down control may translate into behavioral patterns such as impulsivity, risk-taking, novelty-seeking, increased emotional intensity and reactivity in adolescents (Gogtay et al., 2004; Giorgio et al., 2010; Tamura et al., 2012; Rubia, 2013). All of these factors may be functionally adaptive during this developmental period as increased peer-group social focus and orientation toward autonomy is essential in adolescence. However, these factors may simultaneously constitute an increased vulnerability to depressive symptomatology (Ernst and Korelitz, 2009). To alter negative trajectories leading to depressive illness and to avoid the lifelong recurrent pattern of depression, we should intervene with effective prevention and treatment in childhood and adolescence when neuronal plasticity is at its peak and before secondary co-morbidities occur (Hulvershorn et al., 2011).

THE NEUROCIRCUITRY CENTRAL TO THE PSYCHOPATHOLOGY OF ADOLESCENT DEPRESSION

To date, the body of literature on adolescent depression using functional magnetic resonance imaging (fMRI) has shown consistent alterations in the amygdala, the anterior cingulate cortex (ACC), in particular the subgenual portion (sgACC) and the medial prefrontal cortex (MPFC). The amygdala is a limbic structure that plays a key role in emotion-processing and memory formation (Morris et al., 1998; LeDoux, 2007). The sgACC acts as an interface between emotion and cognition with evidence of involvement in both emotion generative and regulatory processing (Seminowicz et al., 2004). The MPFC is implicated in many functions, including emotion regulation, reward processing, memory consolidation, and self-referential processing (Buckner et al., 2008). Both adolescent (Buckner et al., 2008; Yang et al., 2010; Perlman et al., 2012) and adult MDD (Sheline et al., 2001; Cunningham et al., 2002) are associated with amygdalar hyperactivation in response to emotional stimuli, and increased amygdalar activation has been shown to correlate positively with depression severity (Price and Drevets, 2010; Lane et al., 2013). The amygdala has reciprocal connections with the sgACC, which has also been demonstrated to exhibit resting-state hyperperfusion (Ho et al., 2013) and task-related hyperactivation in depressed compared to healthy adolescents (Yang et al., 2009). More recently, functional connectivity (FC) of the sgACC during resting-state (Cullen et al., 2009; Davey et al., 2012a; Connolly et al., 2013) and during emotional processing (Ho et al., 2014) has been assessed to investigate the functioning of neural networks in adolescent depression. Two of these studies showed increased sgACC-amygdala FC in depressed compared to healthy adolescents (Connolly et al., 2013; Ho et al., 2014). It is hypothesized that enhanced bottom-up responses to affectively laden stimuli could be linked to deficits in amygdala and sgACC function and represent heightened emotional reactivity to emotional and social stimuli in adolescent MDD. Similar results have been found in MDD patients in remission (Joormann and Gotlib, 2007; Fritzsche et al., 2010) and in high-risk girls (Joormann et al., 2012), thereby suggesting that limbic and cingulate hyperactivation may be a trait which increases vulnerability to depression. These bottom-up processes could potentially also have negative effects on the development of cognitive control mechanisms involved in physiologic and behavioral coping by sustaining negative affect (Fales et al., 2008; Michl et al., 2013). Depressed individuals often ruminate and have difficulties disengaging from the processing of self-focused, often negatively biased thoughts (Cooney et al., 2010; Manoliu et al., 2013; Mandell et al., 2014). It has been proposed that aberrant switching from self-referential processing involving midline prefrontal structures such as the MPFC to interoceptive processes involving the insula or to goal-directed cognitive processes involving the dorsolateral prefrontal cortex (DLPFC) might contribute to MDD (Manoliu et al., 2013).

The insula is a paralimbic structure implicated in a broad range of different functions (Craig, 2011; Nieuwenhuys, 2012). A dysfunction in the integration of visceral signals to the insular cortex has been suggested in adult depression (Critchley, 2005) and adult MDD is associated with abnormal functional connectivity of the insula (Mutschler et al., 2012; Avery et al., 2013). Interestingly, increased sgACC-insula functional connectivity (Connolly et al., 2013) has been documented in adolescent depression during resting-state, whereas sgACC-insula functional connectivity during emotion processing in this population has been shown to decrease (Ho et al., 2014). This may indicate that altered sgACC-insula connectivity does characterize adolescent MDD, but that the directionality of the functional connections change with brain state (Ho et al., 2014).

Cognitive control areas within portions of the PFC, such as the DLPFC and the ventrolateral prefrontal cortex (VLPFC) have been implicated in adult MDD (Rive et al., 2013). It has been suggested that reduced DLPFC recruitment in depressed adults is present only when the amygdala is overactive, indicating that dysfunction in the DLPFC may not the primary mechanism involved in adult MDD but that amygdalar hyperactivity may have a bottom-up influence on the level of activity in DLPFC (Drevets et al., 2008). The DLPFC does not seem to be as strongly implicated in adolescent as compared to adult MDD (Kerestes et al., 2013). This is in line with the lack of evidence for differences between depressed and healthy control adolescents in both behavioral performance and brain activation in DLPFC during tasks of cognitive control (Davey et al., 2012b; Bora et al., 2013). In fact, cognitive deficits in MDD seem to become more severe with recurrent MDD and are more pronounced in late-life depression (Koenig and Butters, 2014). It must be emphasized that adolescents in general, independent of depressive illness, have functional limitations in top-down control systems compared to adults due to differing frontal development and frontolimbic connections (Gogtay et al., 2004; Giorgio et al., 2010; Tamura et al., 2012; Rubia, 2013). Task-dependent DLPFC activation in adolescents has been shown to measures of impulse control, foresight, and resistance to peer pressure (Andrews-Hanna et al., 2011). The limitations in executive function and cognitive control may thus contribute to the increased risk of depression and certain aspects of adolescent depression symptomatology, but we suggest that these mechanisms are not primarily driving the pathophysiology of adolescent MDD.

It should be mentioned that the dysfunction of specific brain regions described in adolescent depression should not be regarded in isolation, but rather as part of networks of structures functionally interacting together (Greicius, 2008; Hamilton et al., 2013). Studies of adult MDD suggest dysfunction in an extended medial network involved in emotion processing (Price and Drevets, 2012). This network partly overlaps with and is dynamically interacting with the DMN, which is involved in self-referential processing (Buckner et al., 2008; Greicius, 2008; Hamilton et al., 2013). The extended medial network is also functionally interacting with the executive control network implicated in cognitive control of emotions (Phan et al., 2004). Similar network dysfunctions has been partly suggested in adolescent MDD (Kerestes et al., 2013).

Alterations in reward circuitry have also been implicated in the pathophysiology of adolescent MDD (Forbes and Dahl, 2012). Functional MRI studies using reward processing tasks show decreased activation in the striatum and increased activation in MPFC in response to reward in depressed adolescents compared to healthy controls (Forbes and Dahl, 2012). In addition, adolescents with MDD show increased resting-state FC between striatal regions and midline structures (Gabbay et al., 2013). Furthermore, alterations in striatal FC correlate with depression and anhedonic severity (Gabbay et al., 2013). Dysfunctional social reward systems may be particularly implicated in adolescent depression, since depression is often precipitated by social rejection or loss of status in this age-group (Davey et al., 2008). Altered reward circuitry may also be specifically related to anhedonia, which is prevalent but variable among depressed adolescents (Gabbay et al., 2009, 2010, 2012; Geisler et al., 2013). Converging evidence suggests that anhedonia specifically reflects disturbances in a mesolimbic striatum-based reward system in adolescents with MDD, whereas MDD without anhedonia is accompanied by normal function in this circuitry (Gabbay et al., 2013). Anhedonia in adolescence predicts chronicity of MDD (Bennik et al., 2013), is a negative prognostic predictor for treatment response (McMakin et al., 2012), and MDD with anhedonia may constitute more severe type of adolescent depression (Gabbay et al., 2013). The anhedonic form of adolescent depression has a symptom profile similar to adult melancholic depression (Gabbay et al., 2013). In contrast, the adolescent form of depression without anhedonia but with emotion instability/dysregulation, stress reactivity, low impulse control and comorbid anxiety shows a dramatic increase of prevalence at the onset of puberty with a major predominance in girls. This gender effect is hypothesized to be related to estrogen levels and cortisol receptor sensitivity in the brain (Antonijevic, 2006; Paing et al., 2008; Weiser and Handa, 2009; Smith, 2012). The non-anhedonic symptom profile in adolescent depression has similarities with the features of atypical depression in adults according to the DSM system, even though the diagnostic validity is low for atypical depression according to DSM in this age-group (Williamson et al., 2000; Paing et al., 2008). Notably, women have a documented higher frequency of comorbid depression and anxiety disorders, and a threefold higher prevalence of atypical depression compared to men (Silverstein, 2002; Halbreich and Kahn, 2007). The female predominance of depression in adults thus seems to be restricted to the atypical subtype in premenopausal women (Angst et al., 2002; Silverstein, 2002). This contrasts with the pattern seen in postmenopausal women, for whom melancholic MDD is predominant and no gender differences have been identified (Antonijevic, 2006). The literature describes differences in hypothalamic-pituitary-adrenal (HPA) axis function, serotonin and noradrenaline function, immune system activation and treatment response between MDD and atypical depression (Angst et al., 2006; Antonijevic, 2008). Based on this evidence, we hypothesize that the pathophysiological mechanisms involved in atypical depression in women are similar to those in the most common form of depression in adolescent females.

In mid-puberty a 2:1 female to male ratio in depressive disorders emerges (Angold et al., 1998). A large body of literature suggests that an estrogen dependent increase of stress sensitivity and mood instability increases the vulnerability to depression in puberty for girls (Angold et al., 1998, 1999; Steiner et al., 2003; Ter Horst et al., 2009; Weiser and Handa, 2009; Blanton et al., 2012; Smith, 2012).

Summarizing these findings, two possible pathophysiological trajectories leading to adolescent depression emerge. One subtype seems to be driven by *limbic hyperactivation*, related to sustained threat with clinical features such as emotional hyper-reactivity, agitation and dysphoric mood and possible secondary negative effects on the ability to dynamically switch from self-referential processing to interoceptive awareness or goal directed behavior. A second subtype may be driven by *compromised positive reward circuitry* and may be related to an anhedonic subtype of adolescent depression (Gabbay et al., 2013). Based on clinical experience and the literature of atypical versus melancholic depression according to the DSM system (Antonijevic, 2006; Paing et al., 2008), we suggest that the increased prevalence of MDD seen in puberty is mainly constituted by a subtype that best fits the symptomatology of limbic hyperactivation corresponding to the RDoC construct of "sustained threat." The subtype of adolescent MDD that may be more related to dysfunction of reward circuitry seems to remain more stable across different age groups and gender (Antonijevic, 2006; Halbreich and Kahn, 2007). When creating the foundation for an intervention for adolescent depression by determining the hierarchy of the domains of function, it is crucial to identify which of these subgroups to target. In our present work, we chose to focus on the most prevalent type of adolescent depression with clinical features of emotional hyper-reactivity, agitation, and dysphoric mood but without major signs of anhedonia. In the future our manual can be adapted for other types of depression as well.

THE ROLE OF SUSTAINED THREAT IN RELATION TO SYSTEMIC DYSREGULATION AND THE SOMATIC MANIFESTATIONS OF DEPRESSION

The PFC and the amygdala are linked via the vagus nerve to the regulation of metabolic systems (Thayer and Sternberg, 2006). It is hypothesized that a predisposition to amygdala and limbic hyperactivation and decreased vagal control, such as is found in depressive illness, will induce a cascade of dysregulation across multiple systems (Juster et al., 2010). Inflammatory processes (Henje Blom et al., 2011; Maes et al., 2011), glucose–insulin homeostasis, glucocorticoid signaling, oxidative stress, and energy biosynthesis (Thayer and Sternberg, 2006; McIntyre et al., 2007) are examples of systems that are often dysregulated in depression. Over time, this dysregulation can build to an increased risk of developing systemic diseases such as atherosclerosis, heart disease, hypertension, stroke, osteoporosis, deterioration of the immune system, obesity, metabolic syndrome, insulin resistance and Type 2 diabetes (Wolkowitz et al., 2011).

Early childhood experience may be one pathway through which neural circuits underlying depression may become dysregulated. Childhood maltreatment may cause patterns of limbic hyperresponsiveness and increased rumination (Michl et al., 2013), which may consequently lead to altered and sustained physiological responses to stress, including mechanisms of inflammation, oxidative stress, telomerase activity and regulation of neurotrophic factors, growth factors, and neurosteroids (Taylor et al., 2011; Shonkoff and Garner, 2012; Karatsoreos and McEwen, 2013). The effect of chronic childhood abuse and adverse life events on neurosteroid metabolism during development has been especially well studied and described in the RDoC construct of sustained threat (Heim et al., 2000). The implicated mechanism is HPA dysregulation with persistent corticotropin-releasing factor (CRF) hypersecretion, overproduction of adreno-corticotropic hormone (ACTH) in the anterior pituitary and increased glucocorticoid release from the adrenal glands (Heim et al., 2000). Preclinical studies show that increased glucocorticoid secretion progressively reduces neurogenesis and synaptogenesis in the hippocampus (Andersen and Teicher, 2008). This damage to hippocampal neurons then contributes to hippocampal dysfunction and the eventual development of depression (Heim et al., 2000; Kaymak et al., 2010; Dannlowski et al., 2012; Teicher et al., 2012). Regional differences in synaptic development and the establishment of glucocorticoid receptors may also influence the development of other specific regions and functional connectivity among these regions during adolescence. Early life stress has been shown to increase childhood cortisol levels, which predicts decreased amygdala-ventromedial prefrontal cortex (vmPFC) connectivity in adolescence (Burghy et al., 2012). Therefore, there may be a temporal delay between early stress exposure and the clinical manifestations of depression (Andersen and Teicher, 2008).

Smaller hippocampal volumes have been a consistent finding in depressed adults (Kempton et al., 2011) and in early onset depressed adolescents (Kaymak et al., 2010; Hulvershorn et al., 2011). However, in child- and adolescent depression, hippocampal size is positively correlated with the duration of illness, which is not the case in adult depression (Hulvershorn et al., 2011). This may be a compensatory process in the developing brain aimed at neural recovery (Hulvershorn et al., 2011). This is important from a clinical perspective since it implies that reduction of hippocampal volume may be prevented by effective interventions during the sensitive time-period by which this compensatory mechanism is still at work. This finding is also in line with previous data showing that children who are exposed to maternal depressive symptomatology since birth show increased levels of glucocorticoids but not changes in hippocampal volume (Lupien et al., 2011). On the other hand, these children show increased amygdala volumes, which indicates that the amygdala may be particularly sensitive to early life adversity and stress (Lupien et al., 2011).

Based on these findings, we hypothesize that exposure to sustained threat is detrimental to the developing central nervous system. A negative spiral seems to be created wherein amygdala hyperactivity leads to increased metabolic dysfunction, which in turn instigates dysfunction of emotion regulation circuitry and increased sensitivity to threatening cues, further increasing the risk of metabolic consequences (McIntyre et al., 2007). The trajectory of depressive disease starts early and continues unless addressed by effective and targeted interventions (McEwen, 2003; Juster et al., 2010; Dannlowski et al., 2012). We therefore suggest that the first priority in treating pediatric depression should be to normalize amygdala and limbic hyperactivity and ACC dysfunction by specially designed practice as outlined in the later sections of this article.

HIERARCHICAL ORGANIZATION OF THE RDoC DOMAINS OF FUNCTION

We have identified the major RDoC domains of function involved in adolescent depression and organized them in a way that gives priority to domains thought to be driving the psychopathology (see **Table 1**). We propose that the most important factor driving the pathophysiology of mild to moderate adolescent depression without major signs of anhedonia is limbic hyper-reactivity and dysregulation of the amygdala and ACC as previously described. These neural circuits correspond well to **the RDoC construct of sustained threat within the domain of negative valence.** The behavioral unit of analysis of the RDoC construct of sustained threat describes several of the core symptoms of the most common type of adolescent depression: anxious arousal, increased conflict detection, attentional bias to threat, helplessness behavior, punishment sensitivity and avoidance. These mechanisms are supported by the extensive body of literature suggesting an increased risk of adolescent depression as a result of childhood trauma (Andersen and Teicher, 2008; Taylor et al., 2011; D'Andrea et al., 2012; Dannlowski et al., 2012; Gulec et al., 2013) and it is also congruent with the findings that anxious symptomatology often precedes the onset of MDD (Stein et al., 2001) and that anxiety disorders are highly comorbid with MDD in this age group (Keller et al., 1992; Angold and Costello, 1993; Seligman and Ollendick, 1998; Costello et al., 2003; Middeldorp et al., 2005; Olino et al., 2008).

Closely related to the sustained threat mechanism is autonomic nervous system hyper-reactivity **and dysfunction in the domain of arousal and regulatory systems both within the RDoC construct of arousal and sleep-wakefulness.** Neurocircuits related to sleep and to arousal are reciprocally modulating each other. This is represented by reciprocal connections from the amygdala to other limbic structures such as the thalamus and hypothalamus, as well as to cortical structures (McGinty and Szymusiak, 2003; Szymusiak et al., 2007). Insomnia may be secondary to frequent daytime hyper-arousal (Riemann et al., 2010) and it is hypothesized that sleep disturbances precede and are etiologically linked to the emergence of depressive symptoms (Harvey et al., 2011). Persistent sleep disturbance may cause secondary cognitive dysfunctions, daytime tiredness, concentration difficulties, affect dysregulation, emotional reactivity, impulsivity and dysregulation of neuroendocrine and immunological systems and it is negatively related to depression treatment outcome (Manglick et al., 2013).

Dysphoric mood, including sadness, guilt, shame, and low self-esteem are core features of adolescent MDD, which correspond to **the construct loss, within the negative valence RDoC domain.** Worry, rumination, increased self-focus, withdrawal behavior, and impaired sustained attention are examples of other common features of adolescent depression described in the construct loss, that may be secondary to sustained threat mechanisms as previously described. However, it is important to emphasize that several of the behavioral features described within the RDoC construct of loss such as psychomotor retardation, anhedonia, loss of drive (sleep, appetite, libido), and a lack of motivation may constitute a distinct and less prevalent subtype of adolescent depression in which dysfunctional reward circuitry may be implicated. As previously described, we acknowledge that an aberrant reward circuitry exists in adolescent depression as shown in previous functional MRI (Forbes et al., 2007, 2009; Forbes and Dahl, 2012) and magnetic resonance spectroscopy studies (Gabbay et al., 2007). We suggest that these findings may be related to a more severe form of anhedonic depression and that aberrant reward circuitry may not be driving the pathophysiology of mild to moderate adolescent depression, in which the previously described mechanisms of a hyper-reactive limbic system are more dominant.

The DSM-IV definition of MDD includes several more general psychiatric symptoms, which may be part of the DSM diagnostic criteria of other psychiatric disorders as well. These unspecific symptoms may still contribute to and maintain the psychophysiology of depression and be part of the suggested RDoC constructs. Concentration difficulties, for example, are often part of adolescent depression symptomatology and belong to **the construct of attention in the domain of cognitive systems** (Han et al., 2012). Another unspecific symptom associated with adolescent behavior in general is impaired impulse control (Andrews-Hanna et al., 2011) which is described as a **within the cognitive control construct in the domain of cognitive systems** in the RDoC matrix as represented by impaired top-down regulation from DLPFC, VLPFC, and posterior parietal cortex (PPC). The decrease of impulse control in combination with dysphoric mood may be driving secondary comorbidities such as behavioral problems, self-harming behavior, drug abuse, and suicidal actions.

Constructs within the **positive valence system** domain may constitute relevant mechanisms to consider when designing a treatment model for adolescent depression. We hypothesize that dysfunction of mechanisms of **approach motivation** may relate to increased experiential avoidance, which may be involved in sustaining depressive symptomatology. The **reward learning construct within the positive valence system** also describes value-based decision-making behavior that may increase resilience to depressive symptomatology by contributing with behavioral motivation, meaning and direction in the life of the adolescent. Finally, dysfunction within the domain of **social processes** such the constructs of **social communication, perception and understanding self and others and self knowledge** is also important in the treatment of adolescent depression since depressive self-evaluation and extensive negative self-referential processing often impede social connections and a healthy peer group identification that is developmentally important in adolescence.

In summary, we propose the following hierarchy of RDoC constructs in treating mild to moderate adolescent depression without major anhedonia (see also **Table 1**):

1. **Sustained threat** with symptoms of anxious arousal, increased conflict detection, attentional bias to threat and emotion-laden stimuli, helplessness behavior, punishment sensitivity and avoidance.
2. **Arousal and wakefulness** including limbic and autonomic hyperarousal with manifestations such as insomnia and secondary sleep dependent behavioral dysfunctions.

Table 1 | A proposed hierarchy of RDoC constructs relevant in treating mild to moderate adolescent depression without major anhedonia.

RDoC constructs	RDoC domains	Implicated neurocircuitry	Clinical manifestations	Intervention strategies
Driving depressive pathophysiology				
Sustained threat	Negative valence	Limbic hyper-reactivity with dysregulation of the amygdala and the anterior cingulate cortex	Anxious arousal; increased conflict detection, attentional bias to threat, helplessness behavior, punishment sensitivity, avoidance	Stress-reduction by breathing exercises and yoga-based movement
Arousal and sleep-wakefulness	Arousal and regulatory systems	Hypothalamic to thalamic and cortical circuits	Sleep-wake dysregulation and sleep dependent behavioral dysfunctions such as affect regulation, emotional reactivity, impulsivity	Decrease of daytime hyper-arousal by breathing exercises and yoga-based movement. Psycho-education related to sleep
Loss	Negative valence	Sustained amygdala reactivity and decreased DLPFC recruitment. Increased default mode activity	Sadness, guilt, shame, low self-esteem, worry, rumination, increased self-focus, withdrawal behavior	Practice of dynamic shifting from rumination to interoceptive awareness. Cognitive reappraisal techniques
Maintaining depressive psychopathology				
Attention and cognitive control	Cognitive systems	Circuitry involving top down cognitive control: DLPFC, VLPFC, PPC, the insula and limbic system	Concentration difficulties, distractibility. Low impulse control	Practice of attention by body-scans and sitting meditation
Of interest for treatment approach				
Approach motivation	Positive valence	Circuitry involving MPFC, OFC, dorsal and ventral striatum and amygdala		Practice approach behavior rather than experiential avoidance
Reward learning	Positive valence	Circuitry involving OFC and ventral striatum		Core value identification, practicing value-based decision making for behavioral activation
Social communication, perception and understanding self and others and self knowledge	Social processes	Broad range of brain areas, beyond the scope of this table		Practice to care for oneself and others and to receive care/compassion. Practice to communicate emotions. Practice of understanding one-self in relation to others

Since the implied neurocircuitry often overlaps between different RDoC domains and constructs we suggest that only specific neural circuits are targeted for treatment as suggested in the column "implicated neurocircuitry" rather than all of the neurocircuitry described in each construct.

3. **Loss**, including feelings of sadness, guilt, shame, low self-esteem, worry, rumination, increased self-focus, and withdrawal.
4. **Attention and cognitive control** with concentration difficulties, distractibility, and low impulse control.
5. **Approach motivation, mechanisms of reward learning and social processes such as social communication, perception and understanding self and others and self knowledge** are valuable salutogenic life skills which should be addressed in treatment of adolescent depression.

Since a clinical application is time-limited and constrained by aspects of feasibility, we propose the following simplification in the translation of the RDoC constructs to a progressive skills-training with clear treatment goals for adolescent depression (see **Table 1**):

1. Improve autonomic regulation and decreased hyper-arousal and limbic hyper-reactivity (with hypothesized secondary effects on sleep disturbances).
2. Practice attention and interoceptive awareness to enhance dynamic switching away from self-evaluative processing and rumination.
3. Promote emotion recognition by training interoceptive awareness and enhance prefrontal cortical regulation of affect by practicing labeling and communication of emotions.

4. Train top-down cognitive control over affective responses such as negatively biased states of attention, processing, thinking, memory, rumination, and dysfunctional attitudes.
5. Identify intrinsic values to drive pro-social behavior and increase motivation for committed behavioral activation.

PROPOSED THERAPEUTIC TRAINING STRATEGIES BASED ON CURRENT SCIENTIFIC EVIDENCE OF EFFICACY

The first aim of our intervention is to decrease limbic hyper-reactivity and increase autonomic regulation through the promotion of vagal afference. We aim to target neurocircuitry described in the RDoC construct of sustained threat within the domain of negative valence and the dysfunction in the domain of arousal and regulatory systems both within the RDoC constructs of arousal and sleep-wakefulness. ***[Section "Module 1: Calming Down and Creating a Sense of Safety (Weeks 1–3)" for description of the corresponding section of the manual.]***

The nervous system is designed to evaluate risk and match neurophysiological state with the actual risk of the environment (McEwen, 2003). Adolescents with emotional dysregulation often perceive the environment as being dangerous or threatening even when it is safe, which could be a result of early life stress exposure as described in section "The Role of Sustained Threat in Relation to Systemic Dysregulation and the Somatic Manifestations of Depression." This mismatch may result in defensive states, limbic hyperactivation and sympathetic arousal. On the other hand, there is evidence that during the experience of a safe environment, the influence of afferent vagal motor pathways increases, which in turn inhibits the defense mechanisms of the sympathetic nervous system, dampening the stress response (Porges, 2009).

In adult depression (Licht et al., 2008), as well as in adolescent depression, amygdala hyperactivity is related to a decrease of vagal inhibitory control (Yang et al., 2007; Henje Blom et al., 2010) and in depressed patients, a direct association between depression symptom severity and the modulation of cardiovagal activity has been shown (Agelink et al., 2002). It has been proposed that individual differences in heart rate variability (HRV) predict attentional inhibition, which suggests that successful inhibition as well as novelty search may be mediated by cortical inhibitory mechanisms among people with high cardiac vagal tone (Park et al., 2012). Cardiac vagal tone is also associated with both adaptive top-down and bottom-up modulation of emotional processing, which is implicated in depression (Park et al., 2013). From both animal and human neurochemical and neuroimaging studies as well as from studies using vagus nerve stimulation (VNS) – a therapeutic brain stimulation technique sending electrical impulses to the left cervical vagus nerve, which is approved as an adjunct long-term treatment for chronic or recurrent depression – there is considerable evidence that the vagus nerve and its stimulation influence limbic and higher cortical brain regions implicated in mood disorders (Park et al., 2007; Vonck et al., 2014). RSA-biofeedback and breathing training has also been shown to increase vagal modulation and to reduce depressive symptoms (Siepmann et al., 2008; Patron et al., 2012). Increased HRV, and more specifically, respiratory sinus arrhythmia (RSA), has been shown to relate to the level of engagement of coping strategies and social well-being. Moreover, RSA predicts less use of avoidance strategies for regulating negative emotions and more use of socially adaptive emotion-regulation skills in young adults (Geisler et al., 2013).

A few small studies of respiratory biofeedback with focus on assessing RSA have indicated beneficial effects on anxious and depressive symptoms (Patron et al., 2012; Sutarto et al., 2012). Several studies have shown that regular practice of breathing techniques also substantially changes respiratory metabolism and produces psychological effects, such as reduction of chemo-reflex sensitivity (Spicuzza et al., 2000), oxidative stress (Sharma et al., 2003), depressive symptoms (Tweeddale et al., 1994) and symptoms of panic disorder (Meuret et al., 2005; Wollburg et al., 2011; Kim et al., 2012).

We conclude that breathing exercises may be helpful in increasing vagal afference and improving autonomic regulation and for the purpose of the treatment of adolescent depression, yoga-based breathing and movement practices may improve regulatory skills by recruiting vagal and sensory afferent neurocircuitry. These practices may thus have an effect on limbic hyperactivity, break the negative spiral previously described, and prevent the recurrent course of depression. Despite some methodological limitations, there are some preliminary promising results for yoga-based treatment of depressive symptomatology (Pilkington et al., 2005; Ospina et al., 2008; Uebelacker et al., 2010). Limitations of yoga studies for depression include insufficient description of techniques applied as well as problems with control conditions (Pilkington et al., 2005; Shapiro et al., 2007; Dunn, 2008; Uebelacker et al., 2010; Cabral et al., 2011; Balasubramaniam et al., 2012; Khalsa, 2013). No studies have yet been published on yoga based treatment for adolescent depression but two preliminary RCTs, one in a high-school setting (Noggle et al., 2012) and one in a secondary school setting (Khalsa et al., 2012), have focused on yoga as a school intervention for increased wellness and both suggest preventive effects on mental health. Other strategies to calm a hyperactive limbic system such as sensory activation through sound, light (Canbeyli, 2013), smell (Perry and Perry, 2006; Lv et al., 2013), and touch (Hou et al., 2010) are not within the scope of this review, but may have potential anti-depressive effects that need to be further investigated.

The second priority in our intervention is to increase attention skills and shift neural activity from negative self-referencing processing to present-moment sensory and interoceptive awareness. We aim to target parts of the neural circuitry implicated within the RDoC construct of loss in the domain of negative valence and the construct of attention in the domain of cognitive systems. ***[Section "Module 2: Attending and Caring about Our Inner Experience (Weeks 4–6)" for description of the corresponding section of the manual.]***

Adults with MDD who paid less attention to their emotions showed better recovery from MDD (Thompson et al., 2013), but paying too little attention to one's inner state is also thought to be maladaptive for depressed individuals (Thompson et al., 2013). Attending to emotions may be beneficial for individuals with a good capacity to regulate mood, but may be potentially detrimental to those with a low capacity to regulate mood (Lischetzke and

Eid, 2003). Consequently, we suggest that practice of attending emotion is prioritized in the intervention, once regulatory skills have been acquired in section "Module 1: Calming Down and Creating a Sense of Safety (Weeks 1–3)."

The insula may be involved in integrating diffuse feedback from the viscera into cognitive awareness (Nieuwenhuys, 2012). Functional MRI experiments have demonstrated that the insula plays an important role in the experience of pain and the experience of several emotions, including anger, fear, disgust, happiness, and sadness (Craig, 2009). Internal body states are represented in the insula and contribute to our subjective feeling, with insular activity correlating positively with interoceptive accuracy (Critchley, 2005). Depressed adults show less accurate heartbeat perception compared to healthy controls (Furman et al., 2013) and in adults with depressive disorder, training of interoceptive awareness seems to enhance focused attention, which is a cognitive process supported by the ACC and the lateral PFC (Farb et al., 2012). In the context of emotion regulation, increasing interoceptive awareness requires reducing self-evaluative processing. The corresponding neural events during this transition to present-moment sensory awareness include a shifting from midline structures of the PFC to the thalamus, insula, and primary sensory regions (Farb et al., 2012). Training of interoceptive awareness seems to buffer against rumination and negative emotional bias (Farb et al., 2012) and a reduction of emotional limbic hyperactivity has also been shown to be one consequence of mindfulness interventions (Paul et al., 2013). Based on these data, we propose that disengagement from internal self-focus by increasing sensory and introceptive moment-to-moment awareness may be especially helpful for reducing depressive symptoms and vulnerability to depression for adolescents.

As discussed in the previous section, we suggest these skills are cultivated predominantly in contemplative movement practice or in body scans (guided practice of interoceptive awareness) that closely follow a movement practice, rather than in sitting meditation. Four hundred clinical trials on meditation-based interventions for clinical disorders (published between 1956 and 2005) were reviewed in 2007, yet the authors could not make any decisive conclusions with respect to effects on depression due to poor methodological quality (Ospina et al., 2008). In 2007, 15 mindfulness based stress reduction (MBSR) studies for depression and anxiety were also reviewed (Toneatto and Nguyen, 2007). MBSR is 8 week group intervention developed by Kabat-Zinn (1996) containing different components of practice such as body scans, sitting meditation, yoga and informal mindfulness in every day life. Meta-analyses of these studies showed that when active control groups were used, MBSR did not show a reliable effect on depression and anxiety (Toneatto and Nguyen, 2007). More recently, a meta-analyses of mindfulness-based practices for the treatment of adult depression showed relatively small effect sizes on self-assessed depression symptom severity: Cohen's $d = 0.30$ [95% CI, 0.00–0.59] at 8 weeks and Cohen's $d = 0.23$ [95% CI, 0.05–0.42] at 3–6 months (Goyal et al., 2014). Preliminary results from studies applying modified versions of mindfulness based cognitive therapy (MBCT) for the treatment of acute depression have also been published (Eisendrath et al., 2011, 2014; Munshi et al., 2013). However, the MBCT model does not contain any practices that stimulate the vagal afference such as breathing or movement. The implicated mechanisms of change in the MBCT intervention are rather top-down regulatory skills training and meta-cognition strategies, which we propose should not the primary focus in treating adolescent depression. A recent study by Williams et al. (2013) showed that MBCT provided significant protection against depressive relapse, but only for participants who experienced childhood trauma, which supports the notion that sustained threat neuro-mechanisms may increase the risk for recurrent episodes. In comparison to an active control condition and to treatment as usual (TAU), MBCT did not improve symptoms in patients with recurrent depression.

Carmody and Baer (2008) investigated the components contained in the MBSR program and the amount of time these components were practiced between sessions in relation to outcome. Specifically, a strong association was found between yoga and improved mindfulness skills, reduced psychological symptoms (such as anxiety and inter-personal sensitivity), and improved well-being, even though the yoga was practiced on fewer days and for fewer total hours than the other formal practices (Carmody and Baer, 2008). From these reviews, we can conclude that mindfulness-based interventions alone have limited efficacy for treating adult depression, but body-based contemplative practices may be beneficial and warrant further examination.

Studies of mindfulness-based interventions for adolescent depression in clinical settings are rare and the possible neural mechanisms involved have not been studied in this population. One RCT showed a decrease in depression and anxiety symptoms after a MBSR course delivered in a group format for adolescents with heterogeneous diagnoses in a clinical outpatient setting (Biegel et al., 2009). A pilot RCT of acceptance and commitment therapy (ACT) for individual treatment of teenage depression demonstrated greater improvement in depressive symptoms as compared to TAU (Hayes et al., 2011). Recent studies of mindfulness-based group interventions in school settings for teenagers and young adults have also yielded reductions in depression and anxiety-related symptoms. In a non-randomized study of secondary school students, Kuyken et al. (2013) showed that relative to children who participated in the usual school curriculum, children who participated in a mindfulness intervention reported significantly fewer depressive symptoms post-treatment and at 3 months follow-up. In a cluster-RCT of a mindfulness group program for an adolescent school-based population (ages 13–20 years), Raes et al. (2013) demonstrated that effects on depressive symptoms from baseline to post-intervention and from baseline to 6 months after treatment ended were small to medium (both Cohen's $d > 0.30$). These promising early results suggest potential for improvement with contemplative practices carefully tailored for maximum skill uptake and neural effect among adolescents with depression.

The third target is emotion regulation by recognition, labeling and communication of emotions, aiming to improve function in neurocircuits within both the constructs of sustained threat and the construct of loss in the RDoC negative valence domain. ***[Section***

"Module 3: Recognizing, Regulating, and Communicating Emotions (Weeks 7–9)" for description of the corresponding section of the manual.]

We propose that adolescents need to first achieve bottom-up regulatory skills to calm the limbic system with vagal and sensory afferent techniques prior to engaging effectively in training top-down cognitive control strategies. In the previous modules, participants have practiced breathing exercises, yoga-based movement, and body scans to improve attention, interoceptive awareness, and recognition of emotions and their bodily representations. In this module, we introduce more top-down strategies such as labeling emotions. In traditional mindfulness programs for adults, labeling emotions is an inner process that is recommended during meditation when strong emotions arise. It has been shown in adults that mindfulness is associated with enhanced prefrontal cortical regulation of affect through labeling of negative affective stimuli (Creswell et al., 2007), and that during the labeling of emotions, the VLPFC exhibits a dampening effect on the activity of the amygdala (Lieberman et al., 2007; Torrisi et al., 2013). While emotion recognition and labeling are core practices in most mindfulness programs, the skills of communicating emotion or interpreting emotional states in others are not emphasized. We have addressed this limitation by integrating aspects of psychotherapeutic traditions with some evidence of treatment effect for emotional dysregulation and depressive symptomatology in adolescents such as dialectic behavioral therapy (DBT; Bedics et al., 2013) and ACT (Hayes et al., 2010, 2011).

Once the previous regulatory skills have been acquired, the final intervention goal is to introduce practices of top-down cognitive control over affective responses such as negatively biased states of attention, processing, thinking, memory, rumination and dysfunctional attitudes. These functions are related to altered neural circuitry implied in the construct of cognitive control within the RDoC cognitive systems. We also target mechanisms within the RDoC domain of positive valence related to experiential avoidance such as approach motivation and reward learning and within the domain of social processes. ***[Section "Module 4: Core Values, Goal Setting and Committed Action (Weeks 10–12)" for description of the corresponding section of the manual.]***

Cognitive-behavioral strategies for managing depressive symptoms seem to rely on improving the function of the PFC and enhancing the cortico-limbic circuits in modulating emotional processing (Mor and Winquist, 2002; Drevets et al., 2008; Beevers et al., 2010; Cooney et al., 2010; Disner et al., 2011). In the TARA intervention, we emphasize the importance of waiting to introduce this approach once the foundation of the previous "bottom-up" regulatory skills have been consolidated. Our rationale for this is that while strategies of cognitive reappraisal can be effective for emotion regulation in healthy and perhaps depressed adults (Denny and Ochsner, 2013), depressed adolescents have fundamental difficulties with cognitively regulating negative emotion due to developmental and possible depression-related limitations in top-down neural circuitry. Top-down cognitive reappraisal training may be maladaptive and increase risk for rumination and contribute to sustained dysphoric mood (Farb et al., 2012). The top-down model of depression treatment does not take into account that the teenage brain has limited capacity for higher-level executive function. These limitations among adolescents may make them less likely to experience long-term anti-depressive benefit from cognitive control strategies as compared to adults, especially under stressful conditions when limbic hyperactivity tends to override top-down cognitive control. Training adults with depression in executive tasks is associated with increased DLPFC activity during cognitive tasks and with decreased amygdala reactivity in response to emotional stimuli (DeRubeis et al., 2008). However, remission of depression after CBT is associated with decreased, basal DLPFC metabolism, suggesting that recovery might involve the lowering of tonic resting-state activity, allowing for greater reactivity when executive control is recruited (Ressler and Mayberg, 2007; DeRubeis et al., 2008). Since adolescents have limited top-down regulation, we suggest that this mechanism may not be the most effective target to reduce depressive symptomatology. Instead, we prioritize an initial bottom-up regulation strategy to help dampen limbic hyper-reactivity and thereby facilitate the DLPFC contribution to emotion regulation. CBT is the recommended choice of psychological treatment for adolescent depression and has yielded modest effect sizes (Weisz et al., 2006; Watanabe et al., 2007; Reinecke et al., 2009). In a large RCT performed for treatment of adolescent depression, CBT showed a response rate of 43% as compared to 35% for placebo during 12 weeks of treatment, which leaves room for future improvement and development of psychological treatments, such as our approach (Reinecke et al., 2009).

THE CREATION OF A PROGRESSIVE MODULE-BASED TREATMENT PROGRAM FOR ADOLESCENTS WITH DEPRESSION – TRAINING FOR AWARENESS, RESILIENCE, AND ACTION

To enhance the translation of neuroplasticity and neurocircuit retraining research into an effective clinical intervention for adolescent depression in line with RDoC principles, we have integrated approaches drawn from several different paradigms and traditions based on their efficacy and congruence with our scientific theory of change (Cramer et al., 2011). We developed a 12-week group treatment program: we do not aspire to teach meditation or yoga as spiritual practices according to any specific tradition or lineage. The TARA treatment program is only informed by Eastern practices such as meditation and yoga and current evidence on their therapeutic efficacy. The practices have been taken out of their original spiritual and cultural context and then simplified and adapted to fit our therapeutic model and current scientific paradigms. The TARA model has been influenced by practice modalities found in MBSR and MBCT based on evidence of their efficacy for the relevant domains of function as previously outlined (Desrosiers et al., 2013). Some components of the TARA have also been inspired by approaches from CBT, Behavioral Activation, DBT, ACT, Compassion Therapy, and expressive arts therapy. In our proposed research design we include adolescents who are seeking psychiatric care or are under treatment for depressive problems and randomize them to the TARA intervention and TAU or only TAU. Potential participants are screened for depressive symptoms based on DSM-IV, but we do not require a primary MDD diagnosis for inclusion, only a cut-off score of depressive symptoms based on the Children's Depression Rating Scale Revised (CDRS-R; Poznanski, 1996; Guo et al., 2006). It may be argued that this way of identifying participants to the study is paradoxically based on the very same DSM criteria that we are questioning instead of on pure dimensionality. We acknowledge this as a potential limitation in our present design, but find no other solution in the clinical environment in which the study is conducted, and at a time-point when validated self-assessment of RDoC constructs adapted for age and gender are not yet developed. The DSM scheme just allows for a major subtype distinction that will help focus the proposed therapy. We exclude only on the basis of restrictions in the ability to attend the group format and the training content, for example learning disability, psychosis, severe behavioral problems, severe posttraumatic stress disorder (PTSD) and active suicidality but aim in general to be as inclusive as possible when it comes to psychiatric comorbidities.

The TARA program is constructed in four modules, which for future clinical applications will allow for flexibility and adaption based on participant needs so that a module can potentially be continued or repeated until skill uptake is consolidated (Weisz et al., 2011). Each of the 12 TARA sessions is 1.5 h in length and designed for an optimal group size of 10–12 participants. Before the program starts, a session is offered for parents/guardians or other adult persons such as relatives or family friends that are important in the young person's life and who may provide a support system in between sessions. The aim of this introductory session is to outline the overall goals of the program, invite the adults to try some of the practices, and guide them in how they can be of support for the adolescent. Home practice is encouraged and between session treatment support, such as audio-recordings of short, guided meditations, is also provided.

The TARA program is interactively designed and relies on understanding participant behavior given their present context and history (Hayes et al., 2010; Levin et al., 2012). A calm, safe, and respectful group climate is essential and promoted by non-judgmental, empathic, and caring attitudes, and predictability and authenticity on the part of the facilitators. The facilitators must be experienced in leading adolescent group processes and committed to personal contemplative practice in order to effectively model the skills and be able to relate to what the participants are experiencing. The content of the program is transmitted both through implicit and explicit learning. New ways of relating are implicitly taught to the participants by employing skillful and authentic ways of dealing with difficult emotions. Brief psycho-educational modules are offered to provide supportive instruction in lifestyle factors that encourage uptake of the core skills in each module, e.g., physical exercise (Cooney et al., 2013), anti-inflammatory diet/nutrition (Lucas et al., 2013), and adequate sleep (Manglick et al., 2013). In this way, adolescents learn core principles drawn from the theoretical and empirical foundation for the program so they can understand how their brains work and thus develop motivation to practice what they are learning.

The program has been "semi-manualized" to make it replicable and easily implemented in different cultures and settings. TARA is based on the principles of neurocircuitry dysfunction and does not require a strict manualization, as long as these mechanisms of change are deeply understood by the facilitators. This approach increases authenticity and allows for personal teaching strategies, adaptions, and flexibility (e.g., certain practices such as respiratory biofeedback that are consistent with the framework can be incorporated). Each session follows the same sequence: first is "the opening of the circle" in which the group members gather to share experiences from the previous week and go through the homework. Next, there is brief psycho-education, followed by breathing exercises, yoga-based movement and a meditation practice. The sessions end with "the closing of the circle" in which the participants give feedback on the session and are given home practice instructions for the following week. Each session component has a distinct and independent progression throughout the 12 weeks. It is therefore possible to break out each single component into a separate 12-week independent program, which will facilitate future studies of the efficacy of each component such as is possible in adaptive trial designs.

MODULE 1: CALMING DOWN AND CREATING A SENSE OF SAFETY (WEEKS 1–3)

We propose that the first target in correcting the pathophysiology of adolescent depression is to address pathological limbic activity through afferent vagal pathways. We instruct adolescents in breathing techniques and movement practices drawn from yoga that can impact those afferent vagal pathways. As opposed to practices of attending to the breath and increasing awareness of the breath as is typically done in mindfulness-based interventions, we include active breathing practice of a soft "yogic" breathing technique. Slowing down the breathing rate and extending the length of exhalation increases vagus tone and improves autonomic regulation. Our clinical experience suggests that controlling breathing rate and the duration of the breath in this manner promotes feelings of relaxation and well-being. We recommend that participants practice this simple down-pacing and softening of the breath on a daily basis.

After learning to slow and soften their breathing, participants next receive instruction in the use of the "Ujjayi" breathing technique often used in yoga. Instead of using the Sanskrit term "ujjayi" when describing it to the adolescents, we use the term "ocean breath." In our experience, adolescents are more receptive to new mind/body practices when the instructor uses developmentally appropriate language. Ocean breath practice in the TARA intervention is presented as a deep slow rhythmic breathing with the instruction to visualize the inhalation starting from the lower belly, continuing in a wave through the ribcage, upper chest and throat, and followed by exhaling in the opposite order. Inhalations and exhalations are usually approximately equal in duration, but for the purpose of calming the mind, this practice involves a slight extension of the exhalation along with a very brief pause at the end of each inhalation and exhalation, but without tension or any holding of the breath. Both inhalation and exhalation are done through the nostrils (versus through the mouth). Concurrently, narrowing of the throat passage at the glottis level creates a soft and soothing sound that can be described as sounding like the ocean. The duration of the breath is controlled by the diaphragm, and gets extended by practice, but should never create tension or distress. Participants are encouraged to be gentle with themselves and not force the breathing. The breath can also be used to direct attention to certain parts of the body, for example, to increase interoceptive or sensatory capability, release tension or extend the range of movement. Ujjayi breathing is often used in synchronization with movement and an advantage to practicing breathing techniques in combination with movement in a group setting is that a generalization to ways of using the breath practices in everyday life situations is facilitated. For example, participants are encouraged to use ocean breath along with their movements while walking between classes in school or in regulating their emotions in everyday situations (see "Stop-Breathe-Act" exercise in Module 3).

Following basic instruction in the breathing practices, we offer a series of movement practices drawn from yoga asanas that are intended to promote calmness and "grounding." The movements are presented in a non-competitive manner that emphasizes experience versus achievement. We do not expect that the hypothesized antidepressant effect of the practice will arise from the intensity of the physical training such as is highlighted in muscle-building, endurance or aerobic fitness. Instead, we promote specific qualities of the movement practices such as posture, balance, and development of equanimity, and non-straining/non-pushing. We support these attitudes and qualities of physical movement to enhance the development of their psychological counterparts. We also emphasize a focus on interoceptive and sensory awareness, along with ways to use the breath to direct the attention toward unpleasant sensations. When participants feel a painful, unpleasant, or stressful physical sensation, we encourage them to use their breathing practices to turn toward the sensation and explore it instead of avoiding the experience. This strategy can thereby lessen the tension related to "holding" emotional pain, stress, or anxiety. At home, a daily practice is preferred as opposed to more extensive training with longer intervals in between practice sessions. Regular, brief practice may be preferable for impacting change in pathophysiological mechanisms.

The psycho-education part in Module 1 covers stress, breathing physiology, sleep, and a discussion about what really matters in the lives of the participants, i.e., defining one's core-values.

MODULE 2: ATTENDING AND CARING ABOUT OUR INNER EXPERIENCE (WEEKS 4–6)

Module 2 focuses on attention regulation and practices of interoceptive awareness. In these practices, participants receive verbal guidance to practice paying attention to a variety of "objects of attention" (i.e., the stimuli to which one directs attention). The first set of attention objects includes sensory stimuli such as externally oriented sounds, smells and tactile sensations. Progressively, the focus of attention is shifted inward toward more subtle sensations. Interoceptive awareness may include attention to different types of somatic perceptions for example proprioceptive (a sense of where your body is in space), kinesthetic (a sense of body position, weight, muscle tension and movement), pain, and temperature sensations. The practice of attention and interoceptive awareness can be integrated with yoga-based movement and can also be extended to involve any kind of physical activity, such as walking, running or biking, so that it fits with the culture and interests of the adolescent. Gradually, brief practices in stillness, such as body scans and guided sitting meditations are introduced. Focusing on the breath is a traditional meditation practice and shifting from manipulation of the breath to simply attending to it may be a next step after the breathing practice introduced in Module 1.

Traditionally, mindfulness-based interventions aim to increase the capacity to experience a full range of emotions and sensations instead of trying to ease or modify the experience. From our clinical experience of teaching mindfulness-based methods to adolescents with depression, this approach is often initially experienced as overwhelming and can be counter-productive for adherence and compliance to training. It is important to introduce attention training in a manner that is engaging, relevant, and manageable for the depressed adolescent in order to empower them and motivate continued practice. We hypothesize this practice of attending to one's inner sensations may increase the ability to capture early warning signs of stress or depression and prepare the practitioner to become more aware and skillful in handling bodily expressions of emotions, which will be the focus of the next module. Teenagers are often preoccupied with handling peer pressure, are vulnerable to the judgments of others, and seek external reward. Caring for one's own inner experience may increase the capacity for self-compassion and also facilitate empathy and compassion for others, all of which have been shown to increase resilience to depressive problems (Germer and Neff, 2013; Gilbert, 2014). We suggest that the heavy cultural bias to external stimuli and extrinsic value systems may lead to objectification, loss of internal points of references, and increased vulnerability to depressive illness. Thus, we hypothesize that practices of interoceptive awareness can be used to develop the capability to recognize one's own intrinsic values, and by practice make them a foundation for behavior and action (see Module 4).

The educational topics in Module 2 include basic brain function and how the TARA practices promote the brain's capacity to regulate feelings of stress, anxiety and depression. The concept of attention is also explained and how attention can improve with practice. Healthy food and eating habits in relation to glucose regulation and mood are also explained.

MODULE 3: RECOGNIZING, REGULATING, AND COMMUNICATING EMOTIONS (WEEKS 7–9)

The skills training provided in Modules 1 and 2 are continued throughout this module for consolidation and to encourage the application of these practices as a foundation for emotion regulation. Breathing exercises in which exhalation is prolonged are introduced for calming effects and a simple exercise "Stop-Breathe-Act" is practiced with the aim of being able to use breath for emotion regulation in every day life. In Module 3, the practice of interoceptive awareness extends from being focused on body sensation to emotion recognition. The main focus of this module is development of the ability to link bodily sensations to present-moment emotional awareness. As children and adolescents with mood disorders often have alexithymia tendencies (Gulec et al., 2013), externalization techniques and non-verbal forms of describing emotion are included early in this module. For example, emotions can be depicted through artwork so the emotions can be recognized and described in terms of color, texture, shape, and weight. Labeling of emotions is the next step and it is practiced first as a strategy to regulate emotion and then as later as a way to communicate emotion.

The next goal of this module is to use the acquired skills to communicate emotions to others in an empathic, responsible and pro-social way. Practices of recognizing and handling emotions in other people will be practiced. Toward the end of Module 3 there is also an introduction to understanding social triggers that cause negative emotions to arise and a focus on one's own experiential avoidance strategies and how they may impede obtaining desired life-goals.

The education portion of Module 3 focuses on explaining a schematic illustration of how the brain functions. To further enhance the participants' autonomy in their practice and to empower them, they start guiding the breathing, yoga-based movement and brief meditations to each other under supervision of the facilitators.

MODULE 4: CORE VALUES, GOAL SETTING AND COMMITTED ACTION (WEEKS 10–12)

After basic regulatory skills have been acquired, more conventional cognitive reappraisal techniques to skillfully handle negative emotion regulation are introduced. Habitual thought patterns, assumptions, and cultural bias are tested and perspective shifting is practiced. Participants reassess the previously identified social triggers that cause negative emotions to arise for them and how their own experiential avoidance strategies impact their lives. In this last module, there is also an emphasis on summarizing personal core values. This has been a thread throughout the treatment, but it is now addressed directly through written and experiential activities. Each participant is supported in the process of finding out what they intrinsically value and then extending these values to behavior and action oriented toward future short and long-term life goals. Identifying core values may thus serve as a motivational force for sustainable behavioral activation in a way that is meaningful and relevant to the adolescent.

Since adolescents with depression often have social difficulties there are also specific exercises on how to connect and contribute to others, such as teamwork exercises. We investigate different aspects of care and compassion, i.e., toward oneself and others along with the capacity to be able to receive care and compassion. These concepts are practiced in short, guided loving-kindness meditations and by behavioral practices such as "random acts of kindness." The concepts of caring and compassion are also linked back to core values (i.e., we care about what we value and what is really important to us). Caring is also addressed in a more extended perspective. We hypothesize that explicit practices of how to care for each other will increase a sense of connectedness and decrease the sense of loneliness and separation that depressed adolescents often feel. Furthermore, we hypothesize based on our clinical experience that depressed adolescents often feel disconnected from their environment and lack a sense of purpose and meaning. Adolescents are sometimes left alone with relevant questions and concerns about an uncertain future and without the tools or the knowledge of how to be able to connect and contribute in meaningful ways. Consequently, we have integrated these topics throughout the TARA treatment by practicing care for one another and the world around us. Thus, in this last module, these issues are more explicitly addressed and concrete ways to engage and commit are identified and explored.

Finally, great care is given to end the TARA program in a skillful way. Facilitators guide discussions centered on the following questions, among others: "What have I learned?" "How do I move forward from here?" "What do I do if I feel worse again?" The participants are encouraged to create their own personal daily practice aligned with their life goals. In this way, the breathing, yoga-based movement, and meditations are personalized to fit each participant and can be used as a foundation for life as they have been the foundation of the TARA intervention.

SUMMARY

In this conceptual article, we describe the design of a semi-structured, progressive, and individually adaptable program based on the NIMH RDoC criteria for the treatment of adolescent depression without major anhedonia. The program prioritizes the core domains of function hypothesized to drive the pathophysiology of adolescent depression and employs straightforward and feasible treatment strategies that have been selected based on current scientific evidence. A limitation of the RDoC matrix is that the developmental aspects of adolescent depression are not well considered and some of the implied neurocircuitry overlaps between domains and constructs. To maximize time, resources, and feasibility, we therefore suggest specific neural circuits to be targeted in our treatment model rather than the full constructs. We hope that this work may form the basis for a novel and more effective treatment strategy for adolescent depression, as well as open up a discussion on how to take on this challenge. We aim to continue the curriculum development of TARA and to test feasibility and efficacy of this program in clinical populations, as well as study the neuroscientific and systemic regulatory mechanisms of change. Finally, we propose this treatment approach will both effectively treat depression and promote more general long-term health and well-being.

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First-person experience and yoga research: studying neural correlates of an intentional practice

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INTRODUCTION

Recent years have seen a dramatic increase in the scientific study of contemplative practices. While seated meditation practices have historically been at the center of inquiry in contemplative sciences, movement-based practices, such as yoga, t'ai chi, qigong, and others, are currently coming to the forefront of this discourse. In her introduction to the present Research Topic, Schmalzl et al. (2014) introduce movement-based contemplative practices (MBCP) and present their essential qualities: MBCPs are embodied and attentive to kinesthetic and proprioceptive sensations; are structured by intentional movement; and are contemplative, that is, characterized by deliberate observation and non-judgmental awareness.

In this opinion paper, I focus on the necessity of studying intentional and experiential aspects of yoga as a MBCP, and on the role of first-person experiential reports in the neurophenomenological investigation of yoga and other MBCPs. I propose that the difference between yoga as a contemplative practice and yoga as a form of physical exercise needs to be assessed through nuanced investigation of subjective experience aimed at illuminating short- and long-term intentions and goals underlying yoga practice as well as dynamic variations within the lived experience of yoga.

EMBODIMENT AND NEUROPHENOMENOLOGY

Theories of embodiment, such as enaction (Thompson, 2005, 2007; Noe, 2006; Stewart et al., 2010) stress the irreducible foundational links between the mind, the world and the body as conditions of possibility for consciousness. Rooted in the phenomenological tradition of Husserl (1982) and Merleau-Ponty many embodied mind theorists see movement not only as a pragmatic function of interacting with the world, but as a dynamic and plastic way of knowing and as a formative root of one's selfhood and subjectivity (Morris, 2004, 2010). The concept of a "lived body," derived from Merleau-Ponty (2012), reflects subjectivity conditioned by kinesthetic patterns and bodily habits throughout a lifetime. Yoga practice, in this view, consists of systematic change and of deconditioning of the "lived body" from its earlier habit patterns and creating new patterns and neural connections. Contemporary neurophysiological evidence lends support to the embodied mind approaches, placing sensorimotor "coupling" (Thompson and Varela, 2001) between an individual's moving body and the world at the center of research on subjective experience.

Recent research on contemplative practices, predominantly focused on sitting meditation, has suggested a role of sustained contemplative training for processes of neuroplasticity (Manna et al., 2010), self-awareness (Vago and Silbersweig, 2012) attention modulation, (Lutz et al., 2008b; MacLean et al., 2010), and emotion regulation (Lutz et al., 2008a; Sahdra et al., 2011), among others.

Studying yoga as a MBCP would highlight specific contributions of intentional and dynamic bodily processes to embodied cognition, including processes associated with intentional movement, attention to bodily states, and brain changes linked to variations in the experiential "lived body" and in underlying nervous system due to sustained physical and mental asana practice.

Neurophenomenology (Varela, 1996; Lutz and Thompson, 2003) is the preferred method of inquiry for contemporary contemplative neurosciences and empirical studies of embodied and enactive cognition. The defining feature of neurophenomenology is the use of sophisticated objective neurophysiological measurements in conjunction with nuanced first-person methodologies. Within this framework, objective, and subjective data are seen as mutually constraining and informing, and dynamic methods of examining conscious experience are preferred. Despite a historical distrust of first-person reports by cognitive neuroscientists (Nisbett and Wilson, 1977), recent years have seen an important rise in the use of first-person methodologies both in the form of questionnaires and phenomenologically-informed practices (Chalmers, 1999). Cognitive neurosciences have gradually opened to the integration of systematic analysis of first-person reports (Overgaard et al., 2008), and a number of rigorous approaches to subjective data are now being developed. One methodology, known as "elicitation interview" (Petitmengin, 2006), has been used in a number of studies, including an investigation of epileptic aura (Petitmengin et al., 2006) and the generation of scientific insight (Petitmengin, 2007).

YOGA AS CONTEMPLATIVE PRACTICE

While the contemporary form of asana sequences of *Hatha Yoga* is relatively recent (Gard et al., 2014), many schools (such as Ashtanga Yoga and Iyengar Yoga) have referred to the ancient text, Patanjali's *Yoga Sutra* (Miller, 1995; White, 2014), as the philosophical source text defining and situating yoga practice on and off the mat. According to the much cited passage from the *Yoga Sutra*, the definition of the yoga practice is: *citta-vrtti-nirodha,* translated as "cessation of the turnings of thought" (Miller, 1995). The goal of yoga, in the traditional sense, can be conceptualized as a "path to freedom" through "graduate unwinding of misconceptions that allows for fresh perceptions" (Miller, 1995); the approach is similar to the traditional goal of sitting meditation practices, i.e., the concept of *enlightenment.* It would follow, then, that in addition to the expected physical benefits of systematic exercise, yoga would have a number of effects on the mind, and that these effects would resemble at least some of the outcomes observed in meditation research.

One line of inquiry in current meditation research concerns the effort to untangle the distinct effects that different meditation practices may have on the brain. Lutz et al. (2008b) have divided meditation practices into two broad categories of "open monitoring" and "focused attention," and Travis and Shear (2010) have proposed a third category—"automatic self-transcendence." Josipovic (2010) pointed out that some states cultivated by meditation practices are not currently conceptualized by cognitive neurosciences, so the process of taxonomy and classification needs to proceed in a careful and highly interdisciplinary manner. In *hatha* yoga, such as Ashtanga yoga (Jois, 2010), practice is often structured around focused attention on breathing (*pranayama*) and postures (*asana*), while a non-judgmental attitude and acceptance of one's current psycho-physical state can be characterized, in part, as open monitoring. Furthermore, Ashtanga yoga has been linked to the trait of self-transcendence (Fiori et al., 2014), suggesting that at least one, possibly all (focused attention, open monitoring, and self-transcendence), and perhaps other yet unidentified experiential categories can be applied to neurophenomenological yoga research.

INTENTION

An integral part of contemplative practice, intention, has been largely unexplored in contemplative neurosciences. Goals, reasons, and expectations of practitioners need to be taken into consideration in order to elucidate neural correlates of a practice. Intentionality is understood in phenomenology as an "aboutness" of consciousness; consciousness is always a consciousness "of something" (Roy, 1999). Theories of enaction and embodied cognition have incorporated these ideas into a framework of perception and action being oriented, motivated and purposeful within the individual's relationship with the world. In cognitive science, however, intention is often used as a synonym for doing something purposefully, a motivated goal-oriented behavior, with a certain disposition, and expectation. Intentional behavior has been linked to activity in the right posterior temporal superior sulcus network, to the mirror neuron system (Carter et al., 2011), and to the reward system in humans, which involves such structures as ventral striatum (Fliessbach et al., 2007), ventral tegmental area (D'Ardenne et al., 2008), dorsal striatum, putamen, and caudate nucleus (Haruno and Kawato, 2006). What kinds of rewards/expectations can one study in yoga practitioners? Moreover, since contemplative practices, including MBCPs, typically involve long-term commitment, how can one qualify neurophysiological changes before/during/after yoga practice taking into account various possible expectations/rewards associated with an individual practitioner's motivation?

In contemplative practices in general, setting and maintaining of intention plays an important ritualistic and motivational role, especially in the early stages of practice. Within meditation practices, method and intentions vary between stilling focused attention, open monitoring, self-transcendence, and compassion-based training. Recent meditation research has started to unearth some of the neural correlates of intentional contemplative practices. Focused attention meditation recruits attentional networks including insula, anterior cingulate, frontal-parietal regions, and dorsolateral prefrontal cortex (Dickenson et al., 2013). Further, increased functional connectivity between intrinsic and extrinsic networks was reported in practitioners of non-dual awareness (Josipovic, 2014). Finally, recent research on compassion meditation training showed alterations in inferior parietal cortex and DPLFC, networks underlying social cognition and emotion regulation (Weng et al., 2013). Studying neural mechanisms of yoga practice may involve an interaction between processes of intentional reward-oriented behaviors and different kinds of contemplative focus.

However, intention setting in yoga has not been widely studied, despite being an integral part of the practice of some yoga traditions (an opening prayer in Ashtanga yoga being one such example). One phenomenological study of body-based therapeutic practices, including yoga, presented compelling evidence for the role of both long- and short-terms goals and intentions in practitioners and patients, including specific goals of coping with the present situation and general motivations for exploring qualities of embodiment through practice (Mehling et al., 2011).

As a MBCP, yoga shares some of the intentional, motivational and practical elements of meditation. As a form of exercise, it contributes to overall physical health and wellbeing. It is therefore crucial, in order to conduct neurophenomenological research on yoga and to investigate contemplative and intentional dimensions, to factor in various possible short- and long-term intentions and goals that practitioners may set for their practice.

NEUROPHENOMENOLOGY AND YOGA

Lastly, not only long and short-term intentions, motivations and expectations may have an effect on the neural correlates of yoga practice; one's subjective experience may also undergo a number of cognitive-affective changes during practice. Indeed, temporal dynamics of a meditation experience have been shown to change as a function of attentional and awareness focus in the course of short neurofeedback practices (Garrison et al., 2013a). Since real-time neurofeedback or high-resolution neuroimaging is unlikely during yoga practice, autonomic system measures can be employed in lieu of EEGs or brain scans. For instance, a recent study has used heart rate variability measures as a proxy for affect regulation, along with detailed first-person reports and subjective rating scales to show dynamic changes in attention, affect and subjective experience of calm/activation during a yoga session (Mackenzie et al., 2014). Research potential for including first-person reports in yoga research is further illustrated by another recent study where women suffering from breast cancer were initiated into Iyengar yoga practice; participants underwent pre- and post-study interviews and kept a journal for the duration of the study (Thomas et al., 2014), revealing personal perspectives on qualities of embodiment, posture, and loss.

Studying the neural dynamics of embodied contemplative practices in conjunction with fluctuations in first-person experience would provide invaluable insight to outcome measures, and also to the moment-to-moment changes in practice, experience and intention, which in turn will help elucidate underlying brain mechanisms and contribute to development of interventions adapted to the needs of specific target groups (e.g., Individuals undergoing cancer treatment, depression, anxiety, chronic pain, etc…). The "lived body" is changed by MBCPs, and these changes can be qualitatively explored to investigate both effects of specific MBCPs and structure of embodied subjectivity in general. While investigating the therapeutic effect of yoga in various populations has been the approach of choice, studying healthy individuals involved in sustained contemplative yoga practice (Fiori et al., 2014) may illuminate long-term effects of the practice. This approach has been fruitful in meditation research both by selecting "expert" meditators as participants (Nicholson, 2006; Khalsa et al., 2008; Garrison et al., 2013b), and longitudinally, during a 3-month long Shamatha meditation retreat (MacLean et al., 2010; Saggar et al., 2012; Jacobs et al., 2013). Studying "expert" yoga practitioners can illuminate important aspects of the practice, for instance, some advanced yoga practices emphasize the possibility of awareness without sensory content, such as *purusha* in the yogic tradition (Maehle, 2007). This and other aspects of yoga need to be assessed in a phenomenological way. A neurophenomenological approach is needed in order to assess long- and short-term expectations as well as moment-to moment fluctuations during yoga practice and their neural correlates. Lastly, employing not only expert practitioners but also practicing scientists (Desbordes and Negi, 2013) may contribute to more comprehensive and nuanced contemplative neuroscience of yoga and other MBCPs.

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Neuroprotective effects of yoga practice: age-, experience-, and frequency-dependent plasticity

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Yoga combines postures, breathing, and meditation. Despite reported health benefits, yoga's effects on the brain have received little study. We used magnetic resonance imaging to compare age-related gray matter (GM) decline in yogis and controls. We also examined the effect of increasing yoga experience and weekly practice on GM volume and assessed which aspects of weekly practice contributed most to brain size. Controls displayed the well documented age-related global brain GM decline while yogis did not, suggesting that yoga contributes to protect the brain against age-related decline. Years of yoga experience correlated mostly with GM volume differences in the left hemisphere (insula, frontal operculum, and orbitofrontal cortex) suggesting that yoga tunes the brain toward a parasympatically driven mode and positive states. The number of hours of weekly practice correlated with GM volume in the primary somatosensory cortex/superior parietal lobule (S1/SPL), precuneus/posterior cingulate cortex (PCC), hippocampus, and primary visual cortex (V1). Commonality analyses indicated that the combination of postures and meditation contributed the most to the size of the hippocampus, precuneus/PCC, and S1/SPL while the combination of meditation and breathing exercises contributed the most to V1 volume. Yoga's potential neuroprotective effects may provide a neural basis for some of its beneficial effects.

Keywords: yoga, age-related gray matter decline, neuroprotection, magnetic resonance imaging, voxel-based morphometry

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Introduction

Yoga originates in India and is increasingly practiced by Westerners (Barnes et al., 2004, 2008; Saper et al., 2004; Birdee et al., 2008). Several hatha yoga styles are practiced in western societies and most of them encompass physical postures (termed *asana* in Sanskrit), breath control exercises (*pranayama*), and meditation (*dhyana*) including the chanting of Sanskrit mantras.

Yoga offers several documented health benefits including, but not limited to, improvement of depressive, anxious and stressful states and the relief of various painful conditions (Woolery et al., 2004; Lavey et al., 2005; Shapiro et al., 2007; Wren et al., 2011; Li and Goldsmith, 2012). However, the effects of long-term regular yoga practice on the central nervous system had not been explored until recently when it was shown that experienced yoga practitioners have greater GM volume than matched controls in several brain regions including the hippocampus, primary and secondary somatosensory cortices (S1 and S2), insular cortex, anterior, and posterior cingulate cortices (ACC and PCC), inferior and superior parietal cortices, superior temporal gyrus, orbitofrontal cortex (OFC), medial prefrontal cortex, and cerebellum (Froeliger et al., 2012; Villemure et al., 2013). Nevertheless, the cross-sectional nature of these studies does not permit attributing these group differences to yoga practice with certainty, since people with a given brain structure might, for some reason, be drawn to practice yoga.

In the current report, we revisit our data set to address whether the number of years of yoga experience, the amount of weekly yoga practice, and the different aspects of yoga practice impact specific brain regions. Brain differences related to experience and amount of practice within a group of yoga practitioners would suggest that yoga contributes to changing brain anatomy. Indeed, both short-term and long-term increased training and/or performance have been associated with GM increases in human adults in a wide range of cognitive tasks (Maguire et al., 2000; Golestani et al., 2002; Mechelli et al., 2004; Lazar et al., 2005; Draganski et al., 2006; Holzel et al., 2008; Grant et al., 2010) and motor skills (Sluming et al., 2002; Draganski et al., 2004; Driemeyer et al., 2008) in the brain areas involved in those tasks.

Additionally, if different aspects of yoga practice such as postures, breath control techniques, and meditation contributed differently to brain changes it would further suggest that yoga practice contributes to changing brain anatomy. For example, meditation and physical activity are associated with structural differences in brain regions that do not completely overlap. Meditators were repeatedly shown to have larger hippocampal (Holzel et al., 2008; Luders et al., 2009, 2013a,b), insular (Lazar et al., 2005; Holzel et al., 2008; Luders et al., 2012), and left inferior temporal gyrus volume than controls (Holzel et al., 2008; Luders et al., 2009; Leung et al., 2013), while a recent review of the literature revealed that greater cardiorespiratory fitness and physical activity were most consistently associated with larger hippocampal and prefrontal GM volume (Erickson et al., 2014). Given that hatha yoga is a meditative practice embodied in physical postures, it is likely that we could uncover brain areas whose GM is more likely influenced by either postures, breath control, meditation, or different combinations of these.

Finally, previous studies have shown that global brain GM declines with age (Good et al., 2001; Salat et al., 2004; Ziegler et al., 2012) while physical activity and cardiovascular fitness (Colcombe et al., 2003; Tseng et al., 2013), as well as meditation (Lazar et al., 2005; Pagnoni and Cekic, 2007; Luders et al., 2015) have been associated with age-related neuro-protection. In the current report we evaluate whether yoga practice also offers a global age-related protective effects on brain GM volume, since yoga encompasses both a physical and a meditative component. Together, such findings would strongly suggest that yoga practice

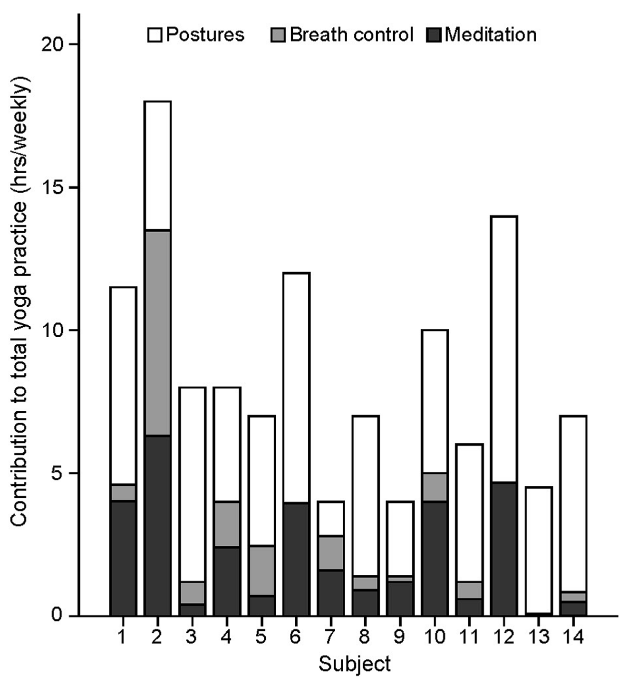

FIGURE 1 | Repartition of yoga practice into its three main components. Number of hours devoted weekly to yoga postures, yoga-related meditation, and separate breath control exercises (excluding breath awareness during postures) for each yoga practitioner. Only the time devoted to the practitioners's personal practice (excluding teaching) are reported.

TABLE 1 | Group matching criteria and yoga practice characteristics.

	Yogis ($N = 14$)	Controls ($N = 14$)	
Sex	Five males Nine females	Five males Nine females	
Handedness	Nine right-handed Five left handed	Nine right-handed Five left handed	
Age (years)	37.0 ± 6.6	36.7 ± 7.3	t(df = 26) = 0.11; p = 0.913
Body mass index	21.6 ± 2.1	22.6 ± 2.8	t(df = 26) = 1.12; p = 0.271
Education (years)	15.9 ± 1.6	15.5 ± 2.1	t(df = 26) = 0.61; p = 0.548
Exercise (h/week)	5.2 ± 3.1	4.7 ± 3.5	t(df = 26) = 0.41; p = 0.684
Yoga experience (years)	9.6 ± 2.8 Range: 6–16		
Weekly yoga practice (h/week)	8.6 ± 4.1 Range: 4–18		
Physical postures (%)	66 ± 21		
Concentration and meditation (%)	23 ± 14		
Breath control exercises (%)	11 ± 12		
Yoga teachers (N)	11		
Teaching (h/week)	9.1 ± 5.1 Range: 3–17.5		

Values are means ± SD.

impacts the brain rather than yoga practitioners having fundamentally larger brain volumes in certain areas leading them to adopt yoga.

Materials and Methods

Participants

This study was approved by McGill University Institutional Review Board. Data were drawn from the same study population described in Villemure et al. (2013). We recruited 14 experienced yoga practitioners from ads posted at yoga studios in Montreal, Canada. The study was open to all types of yoga that integrated physical postures, breath control exercises (minimally breath awareness during postures), and concentration/meditation practices including chanting Sanskrit mantras. During a telephone screening we asked yoga practitioners several questions about their yoga practice and experience. Subjects were questioned about the number of years they had been practicing yoga (experience) and asked to evaluate separately how many hours/week they devoted to their current personal yoga practice and to the teaching of yoga if they were yoga teachers. Subjects were then asked to report what proportion of their current personal weekly yoga practice (excluding teaching) consisted of these three subcomponents: postures, stand-alone breathing exercises, and yoga-related meditation including chanting (**Figure 1**). Fourteen physically active controls were recruited from ads posted on McGill's online classifieds and were individually matched to yogis in terms of sex, age, body mass index, handedness, education, and exercise level outside of yoga (**Table 1**). Applicants were excluded if they currently suffered from or had a history of claustrophobia, chronic pain, chronic systemic diseases, psychiatric, or neurological disorders, or if they were pregnant or breast-feeding, regular smokers or regular users of marijuana, alcohol, or any other recreational drugs, or taking analgesics or anti-depressants. Controls were excluded if they had any previous experience with yoga, meditation or martial arts. All participants provided written informed consent and received monetary compensation for their participation.

MRI Acquisition

Subjects participated in one MRI scanning session including a 10-min anatomical scan and a 15-min diffusion tensor imaging (DTI) scan (DTI results are reported elsewhere; Villemure et al., 2013). Participants wore earplugs to protect them from the scanner noise and their heads were immobilized. Brain images were acquired using a 3 Tesla Siemens Trio (Siemens, Erlangen, Germany) with a standard 12-channel head coil. T1-weighted images were acquired for each subject using a 3D MP-RAGE (Magnetization Prepared Rapid Acquisition by Gradient Echo) sequence [inversion time (TI) = 900 ms, repetition time (TR) = 2300 ms, echo time (TE) = 2.98 ms, flip angle = 9°, filed of view (FOV) = 256 mm; voxel size 1 mm^3).

Voxel-Based Morphometry (VBM) Preprocessing

Anatomical images were preprocessed with the VBM8 toolbox[1] for SPM8[2], running on Matlab (R2007a, The Mathworks, Natick, MA, USA). Details are reported in Villemure et al. (2013) but briefly, images were first bias corrected, tissue classified, and spatially normalized to the MNI space to allow comparison of voxel-based morphometry (VBM) results across studies. The voxel values were multiplied by the non-linear components derived from the spatial normalization to allow for the comparison of the absolute amount of GM volume corrected for individual brain sizes. The modulated volumes were smoothed with a Gaussian kernel of 8 mm full width at half maximum (FWHM).

Correlating Total GM Volume with Age in Yogis and Controls

Total GM volume [including the cerebellum and expressed as % of total intracranial volume (TIV)] was correlated with age separately for each group using Pearson correlations in SPSS PASW Statistics 18.0.

Effects of Years of Yoga Experience and Hours of Weekly Yoga Practice on Brain GM Volume

For the yoga practitioners, we performed two separate whole-brain VBM regression analyses while controling for age and using the number of years of yoga experience and the weekly amount (hours) of yoga practice as predictors [voxel-wise threshold $p < 0.001$, cluster corrected at $p < 0.05$ using random-field-theory (RFT)].

Examining Which Aspects of Yoga Practice Best Predict GM Volumes of the Brain Areas that Correlate with Weekly Amount of Yoga Practice

Once the significant clusters related to the number of hours of weekly yoga practice were identified in the whole-brain regression analyses, we extracted their volumes (in arbitrary units) for each yoga practitioner using MarsBar toolbox for SPM and used the number of weekly hours devoted to the practice of postures, breath control, and yoga-related meditation to determine which aspect or combination of aspects of the total personal yoga practice (excluding teaching) best predicted the size of the identified brain regions using standard multiple regression analyses (SPSS PASW Statistics 20.0) and commonality analyses (SAS 9.3). Regression commonality analysis enables the partitioning of the R^2 effect sizes into the effects uniquely explained by each predictor and the effects commonly explained by all possible combination of predictors (Seibold and McPhee, 1979; Reichwein Zientek and Thompson, 2006). Such analyses were not possible for the number of years of yoga practice for lack of a good estimate of life-time practice in the three different spheres of practice (postures, breath control, and meditation).

[1] http://dbm.neuro.uni-jena.de/vbm/

[2] http://www.fil.ion.ucl.ac.uk/spm/

Additional Correlation Analysis

The number of years of yoga experience was correlated with the number of hours spent teaching yoga each week using Pearson correlations in SPSS PASW Statistics 18.0.

Results

Long-Term Yoga Practice May Have Prevented the Typically Observed Age-Related Decline of GM

In controls, whole brain GM negatively correlated with age [GM volume (**Figure 2**): $r = -0.716$, $p = 0.004$]. In yogis there was no such correlation [GM volume (**Figure 2**): $r = -0.18$, $p = 0.539$]. However, the differences in slopes did not reach statistical significance [group x age interaction: $F(1,24) = 2.555$, $p = 0.123$].

GM Volumes of Several Brain Regions Are Related to the Number of Years of Experience and the Number of Hours of Weekly Yoga Practice

The whole brain regression analyses conducted in yogis revealed that the number of years of yoga experience was positively correlated with GM volume in clusters located in the left mid-insula, left frontal operculum (Brodmann area [BA] 44), right middle temporal gyrus (BA 21) and left OFC (BA 47; **Figure 3**). The current weekly amount of yoga practice was positively correlated with GM volume in clusters located in the right primary somatosensory cortex/superior parietal lobule (S1/SPL), left hippocampus, midline precuneus/PCC, and right primary visual cortex [V1, (BA 17)] (**Figure 4**).

Subcomponents of Weekly Yoga Practice Differentially Predict GM Volumes in the Brain Areas Found to Correlate with Total Weekly Yoga Practice

The number of hours devoted weekly to yoga postures, yoga-related meditation, and stand-alone breath control exercises for

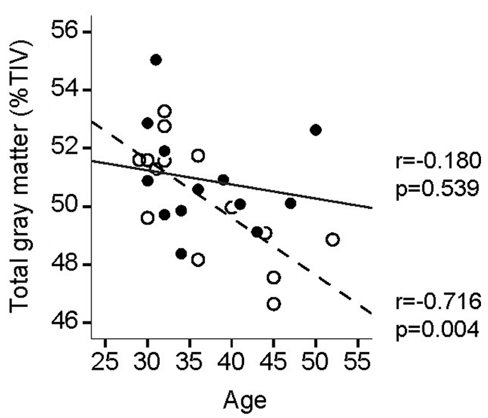

FIGURE 2 | Age-related whole brain gray matter (GM) volume decline. Full circles and full fit line, yogis; open circles and dotted fit line, controls.

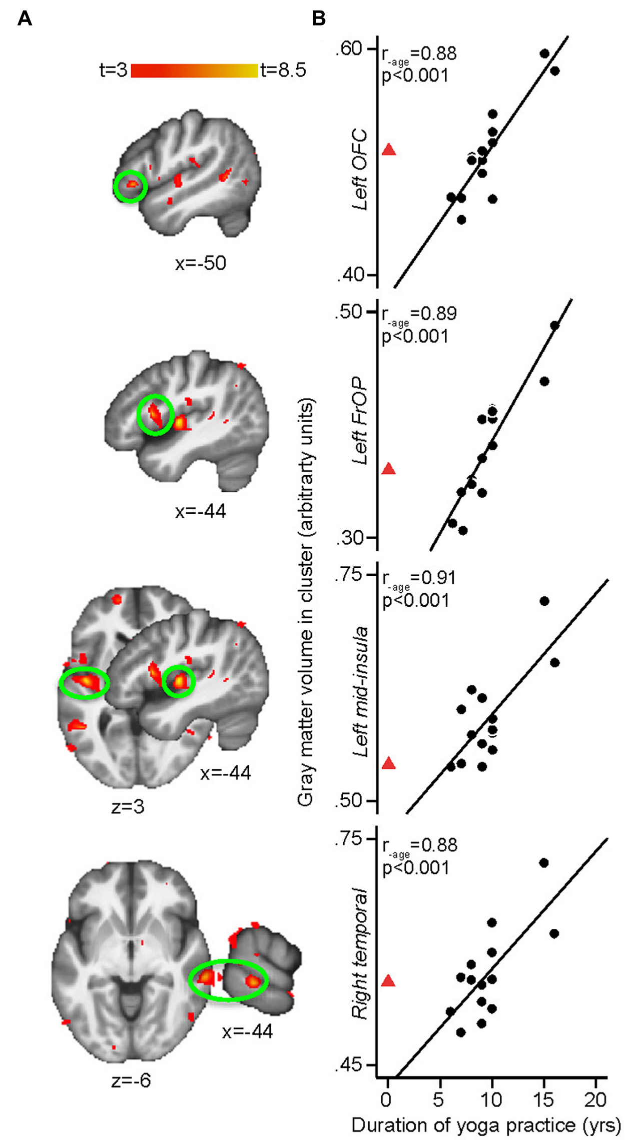

FIGURE 3 | (A) Whole-brain voxel-based morphometry (VBM) regressions with duration (in years) of yoga practice controlling for age. Duration of yoga practice is associated with more GM in the left insula [peak *x, y, z* MNI coordinates: –44, –12, 3; *t*(peak) = 8.38; cluster size: 1374 mm^3, *p*(cluster) = 0.002], left frontal operculum (BA 44) [–44, 11, 10; *t*(peak) = 7.57; cluster size: 263 mm^3, *p*(cluster) = 0.006], right middle temporal gyrus (BA 21) [64, –31, –6; *t*(peak) = 7.00; cluster size: 557 mm^3, *p*(cluster) = 0.011], and left orbitofrontal cortex (OFC; BA 47) [–50, 27, –3; *t*(peak) = 6.53; cluster size: 165 mm^3, *p*(cluster) = 0.018]. Results are cluster-corrected at $p < 0.05$. **(B)** Scatterplots show the extracted mean GM values in the significant clusters plotted against years of yoga practice for each yoga practitioner (arbitrary units, a.u.). Full black circles illustrate individual yoga practitioners and fit line shows regression line across the yoga group. Red triangle shows the mean of control values extracted from the same GM cluster (i.e., representing zero year of yoga practice). The red triangle is not included in the regression with GM, but shows the natural extension at 0 year of yoga practice (extrapolated from control subjects) and is displayed here demonstrate that no yoga experience and the most yoga experience fall onto the opposite end of the same spectrum. Displayed *R*-values are derived from correlating the mean GM in each significant cluster with yoga duration, while controlling for age (SPSS, two-tailed *p*-values).

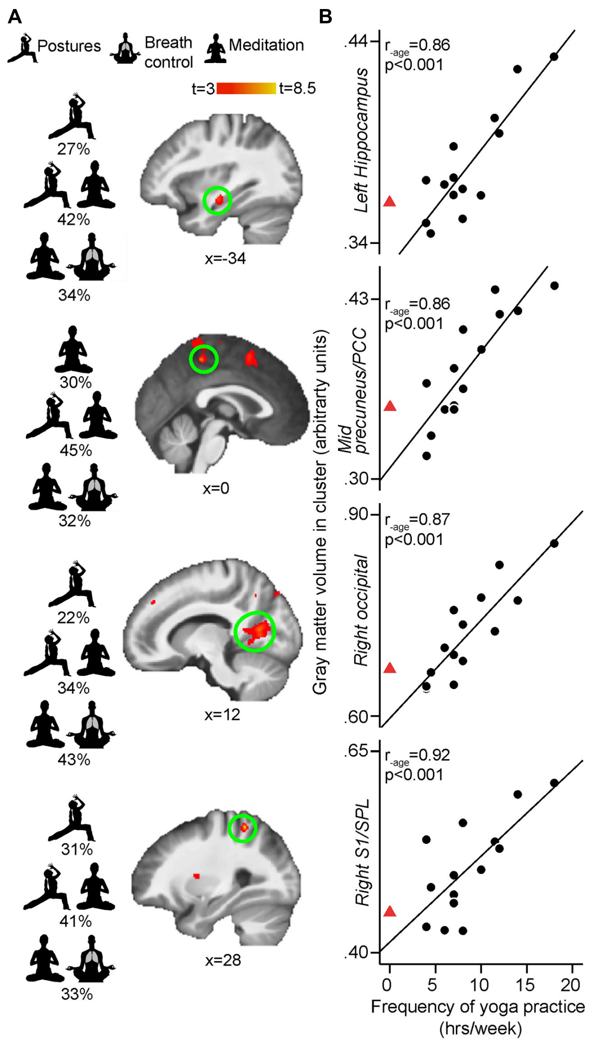

FIGURE 4 | (A) Whole-brain VBM regressions with frequency (hours per week) of yoga practice controlling for age. Increased frequency of yoga practice is associated with more GM in right S1/SPL (BA 7/5) [peak *x, y, z* MNI coordinates: 28, –45, 57; *t*(peak) = 8.17; cluster size: 172 mm^3, *p*(cluster) = 0.005], left hippocampus [–34, –16, –14; *t*(peak) = 6.20; cluster size: 138 mm^3, *p*(cluster) = 0.02], mid precuneus/PCC (BA 7/31) [0, –37, 52; *t*(peak) = 6.15; cluster size: 88 mm^3, *p*(cluster) = 0.033], and right occipital cortex (BA 17) [12, –63, 12; *t*(peak) = 5.79; cluster size: 499 mm^3, *p*(cluster) = 0.013]. Results are cluster-corrected at $p < 0.05$ and displayed on study average brain ($n = 28$). SPL, superior parietal lobule; PCC, posterior cingulate cortex. The main aspects or combination of aspects of yoga practice contributing to each GM volume size according to the regression commonality analyses are depicted to the left of the brains. **(B)** Scatterplots show the extracted mean GM values in the significant clusters plotted against frequency of yoga practice for each yoga practitioner (arbitrary units, a.u.). Full black circles illustrate individual yoga practitioners and fit line shows regression line across the yoga group. Red triangle shows the mean of control values extracted from the same GM cluster (i.e., representing zero weekly hour of yoga practice). The red triangle is not included in the regression with GM, but shows the natural extension at 0 hour/week of yoga practice (extrapolated from control subjects) and is displayed here to demonstrate that no yoga practice and the most yoga practice falls onto the opposite end of the same spectrum. Displayed *R*-values are derived from correlating the mean GM in each significant cluster with yoga frequency, while controlling for age (SPSS, two-tailed *p*-values)

each yogi are presented in **Figure 1** and were used in separate standard multiple regression analyses to determine which factor or combination of factors best predicted the volumes of the left hippocampus, right S1/SPL, right V1, and midline precuneus/PCC. The correlations between variables are shown in **Table 2**. Multicollinearity was minimal here since there were no significant correlations between predictor variables except for a tendency toward a positive correlation between the number of hours devoted to meditation and breath control exercises. The prediction models for all four regions using all three predictors were statistically significant [hippocampus: $F(3,10) = 8.848$, $p = 0.004$; S1/SPL: $F(3,10) = 3.948$, $p = 0.043$; V1: $F(3,10) = 10.631$, $p = 0.002$; precuneus/PCC: $F(3,10) = 14.529$, $p = 0.001$] indicating that the prediction of these four brain GM volumes using these three aspects of yoga practice was accomplished better than can be expected by chance alone. These results remained significant when using a criterion *p* adjusted for the number of regression analyses performed ($p < 0.0125$) except for S1/SPL. Detailed multiple linear results are shown in **Table 3**.

Predicting Hippocampal Volume

The model including the three predictors accounted for approximately 73% of the hippocampal volume variance. The *Beta* coefficient with large structure coefficients indicated that the number of hours devoted weekly to the practice of postures was a good predictor of hippocampal GM volume (Reichwein Zientek and Thompson, 2006). Product measures enable rank ordering of variable importance based on the partitioning of the regression effect (Nathans et al., 2012). These values indicated that the practice of postures followed by yoga-related meditation were the best predictors of hippocampal GM volume. This was confirmed by the commonality analysis results (**Table 4**) showing that nearly half (42%) of the variance in hippocampal GM volume explained by the predictors was common to postures and meditation.

Predicting S1/SPL Volume

The model including the three predictors accounted for approximately 54% of the volume variance of S1/SPL with the number of hours devoted to postures having the greatest influence (highest *Beta* with a large structure coefficient). This was confirmed by the product measure value and the commonality analysis showing that 31% of the variance explained by the predictors was explained by postures alone while 41% was explained by the combination of postures and meditation.

Predicting V1 Volume

The model including the three predictors accounted for about 76% of V1 volume variance. The *Beta* coefficients accompanied by large structure coefficients indicated that both postures and breath control exercises were good predictors of V1 volume. However, the product measure coefficients revealed that all three measured dimensions of yoga practice almost equally contributed. The commonality analysis showed that these factors worked best in combination with nearly half (44%) of the explained variance of V1 volume being explained by the combination of meditation and breath control exercises.

Predicting Precuneus/PCC Volume

The model including the three predictors accounted for approximately 81% of the volume variance of precuneus/PCC. Yoga-related meditation was by far the best predictor of GM precuneus/PCC volume (high beta coefficient, large structure coefficient, and product measure value). This was confirmed by the commonality analysis revealing that nearly a third of the explained variance of the precuneus/PCC GM volume was explained by meditation alone, and 45% by the combination of meditation and postures.

In summary, the combination of postures and meditation contributed the most to the size of the hippocampus, precuneus/PCC, and S1/SPL while the combination of meditation and breath control exercises contributed the most to V1 size (**Figure 3**).

The More Experienced Yogis Spend More Time Teaching Yoga Each Week

If we exclude an outlier who had the least amount of yoga experience but was teaching many hours/week and one teacher for whom we had no data about the number of hours of weekly teaching, we find a positive correlation between the number of years of yoga experience and the number of hours spent teaching yoga each week ($R = 0.679$; $p = 0.015$, 2-tailed; $N = 12$).

Discussion

These data suggest that yoga practice has a neuroprotective effect against the well-documented age-related whole-brain GM degradation, which was evident in our control group. The data also revealed that increasing experience (years of yoga practice) had a differential effect on the brain than did increasing weekly hours of yoga practice. Whole-brain regression analyses showed that more years of yoga experience was associated with increasing GM volumes in clusters located in the left insula, left frontal operculum, right middle temporal gyrus, and left OFC, while more hours devoted to yoga weekly was associated with increasing GM volumes in the right S1/SPL, left hippocampus, midline precuneus/PCC, and right V1 cortex. Finally, postures, breathing exercises, and meditation contributed differently to the structural changes of the four brain areas associated with the amount of weekly yoga practice, consistent with the different nature of the processing taking place in those structures.

TABLE 2 | Correlation matrix associated with the multiple regression analysis.

	Postures	Yoga-related meditation	Stand-alone breath control exercises
Postures		$r = 0.332$, $p = 0.246$	$r = -0.246$, $p = 0.396$
Yoga-related meditation			$r = 0.525$, $p = 0.054$
S1/SPL	$r = 0.523$, $p = 0.054$	**$r = 0.611$, $p = 0.020$**	$r = 0.337$, $p = 0.238$
V1	$r = 0.506$, $p = 0.064$	**$r = 0.754$, $p = 0.002$**	$r = 0.525$, $p = 0.054$
Hippocampus	**$r = 0.591$, $p = 0.026$**	**$r = 0.729$, $p = 0.004$**	$r = 0.393$, $p = 0.164$
Precuneus/PCC	**$r = 0.554$, $p = 0.040$**	**$r = 0.854$, $p = 0.000$**	$r = 0.358$, $p = 0.208$

Pearson correlations between the different independent variables (predictors) as well as between the independent and dependent variables. Listed p-values are two-tailed. Significant results are bolded. S1, primary somatosensory cortex; SPL, superior parietal volume; V1, primary visual cortex; PCC, posterior cingulate cortex.

TABLE 3 | Multiple regression results.

	R	R^2	Adjusted R^2	B	Beta	p	r	r^2	r_{sp}	r_{sp}^2	r_{struc}	r_{struc}^2	PM
Hippocampus													
Postures	0.852	0.726	0.644	0.007	0.549	0.024	0.591	0.349	0.441	0.194	0.694	0.481	0.324
Meditation	0.852	0.726	0.644	0.005	0.372	0.144	0.729	0.531	0.262	0.069	0.856	0.732	0.271
Breath	0.852	0.726	0.644	0.005	0.333	0.175	0.393	0.154	0.241	0.058	0.461	0.213	0.131
S1/SPL													
Postures	0.736	0.542	0.405	0.015	0.510	0.084	0.523	0.274	0.410	0.168	0.711	0.505	0.267
Meditation	0.736	0.542	0.405	0.008	0.275	0.386	0.611	0.373	0.194	0.038	0.830	0.689	0.168
Breath	0.736	0.542	0.405	0.010	0.318	0.307	0.337	0.114	0.230	0.053	0.458	0.210	0.107
V1													
Postures	0.873	0.761	0.690	0.017	0.512	0.024	0.506	0.256	0.411	0.169	0.580	0.336	0.259
Meditation	0.873	0.761	0.690	0.012	0.335	0.157	0.754	0.569	0.236	0.056	0.864	0.746	0.253
Breath	0.873	0.761	0.690	0.018	0.475	0.050	0.525	0.276	0.344	0.118	0.601	0.362	0.249
Precuneus/PCC													
Postures	0.902	0.813	0.757	0.006	0.337	0.076	0.554	0.307	0.271	0.073	0.614	0.377	0.187
Meditation	0.902	0.813	0.757	0.013	0.704	0.005	0.854	0.729	0.497	0.247	0.947	0.896	0.601
Breath	0.902	0.813	0.757	0.001	0.071	0.713	0.358	0.128	0.052	0.003	0.397	0.158	0.025

R, raw regression coefficient; B, raw regression coefficient; Beta, standardized regression coefficient; p, probability; r, zero-order correlation (Pearson correlation); r_{sp}, semipartial correlation; r_{sp}^2, commonality coefficient for the unique effects; r_{struc}, structure coefficient (r/R); PM, product measure (r × Beta). S1, primary somatosensory cortex; SPL, superior parietal volume; V1, primary visual cortex; PCC, posterior cingulate cortex.

TABLE 4 | Commonality matrix.

	Coefficient	% TOTAL
Hippocampus		
Unique to postures (x1)	0.194	26.722
Unique to meditation (x2)	0.069	9.504
Unique to breath control (x3)	0.058	7.989
Common to x1, x2	0.308	42.424
Common to x1, x3	−0.058	−7.989
Common to x2, x3	0.250	34.435
Common to x1, x2, x3	−0.095	−13.085
Total	0.726	100
S1/SPL		
Unique to postures (x1)	0.168	30.996
Unique to meditation (x2)	0.038	7.011
Unique to breath control (x3)	0.053	9.779
Common to x1, x2	0.223	41.144
Common to x1, x3	−0.053	−9.779
Common to x2, x3	0.177	32.657
Common to x1, x2, x3	−0.064	−11.808
Total	0.542	100
V1		
Unique to postures (x1)	0.169	22.208
Unique to meditation (x2)	0.056	7.359
Unique to breath control (x3)	0.118	15.506
Common to x1, x2	0.260	34.166
Common to x1, x3	−0.095	−12.484
Common to x2, x3	0.331	43.495
Common to x1, x2, x3	−0.078	−10.250
Total	0.761	100
Precuneus/PCC		
Unique to postures (x1)	0.073	8.979
Unique to meditation (x2)	0.246	30.258
Unique to breath control (x3)	0.002	0.246
Common to x1, x2	0.366	45.018
Common to x1, x3	0.009	1.107
Common to x2, x3	0.259	31.857
Common to x1, x2, x3	−0.142	−17.466
Total	0.813	100

S1, primary somatosensory cortex; SPL, superior parietal volume; V1, primary visual cortex; PCC, posterior cingulate cortex.

Age-Related Global GM Matter Decline

Global brain GM declines with age (Good et al., 2001; Salat et al., 2004), and we found this same decline in our physically active healthy controls but not in the yoga group suggesting that yoga practice may offer a neuroprotective effect against age-related GM loss. However, because the differences in age-related GM decline slopes did not reach statistical significance, possibly due to a lack of power ensuing from our relatively small sample size, this finding should be interpreted with caution. Physical activity and cardiovascular fitness (Colcombe et al., 2003; Tseng et al., 2013), as well as meditation (Lazar et al., 2005; Pagnoni and Cekic, 2007; Luders et al., 2015) offer similar neuroprotective advantages, suggesting that both the physical and meditative aspects of yoga may contribute to the protection against age-related decline in GM. The differential influence of postures and meditative practices on the brain, as shown here, support that both physical and mental activities contribute to total volume changes, but may occur in partially separate regions. Whether yoga, which encompasses both a physical and a meditative aspect, offers increased protection over meditation or physical activity alone remains an open question.

GM Volume Related to Yoga Experience

More GM related to long-term experience or skill proficiency have been reported in a number of populations like meditators (Lazar et al., 2005; Holzel et al., 2008; Grant et al., 2010; Luders et al., 2013a), orchestra musicians (Sluming et al., 2002), taxi drivers with extensive navigation experience (Maguire et al., 2000), and bilingual individuals (Mechelli et al., 2004). Here, the number of years of yoga experience was positively correlated with GM volume in clusters located in the left mid-insula, left frontal operculum, right posterior middle temporal cortex, and left OFC suggesting that persevering on the yoga path continues to bring positive changes to the brain even in experienced practitioners (minimum experience here was six years). GM volumes or cortical thickness within the insula, temporal cortex, and OFC, albeit sometimes at different locations, have been reported to correlate with both yoga and meditation experience (Lazar et al., 2005; Holzel et al., 2008; Vestergaard-Poulsen et al., 2009; Froeliger et al., 2012; Fox et al., 2014).

Experience-Related Findings Were Mostly Lateralized to the Left Hemisphere

In the current study, most brain regions' volume correlating with the number of years of yoga experience was located in the left hemisphere. This was also the case in another study of hatha yoga practitioners with strikingly similar age, education, and yoga experience (Froeliger et al., 2012). According to the homeostasis model of awareness, the left forebrain is associated with energy nourishment, parasympathetic activity, relaxation, approach behaviors, and group-oriented (affiliative) emotions, while the right forebrain is associated with energy expenditure, sympathetic activity, arousal withdrawal (aversive) behavior and individual- oriented (survival) emotions (Craig, 2009). This model fits with an accumulating body of psychophysical literature finding that the left and right forebrains are associated with positive and negative affect, respectively, and with findings related to meditation on joy and happiness, two positive states, reported to almost exclusively activate brain regions in the left hemisphere (Lou et al., 1999). This suggests that increasing years of yoga practice progressively tunes the brain toward a parasympathetically driven mode and positive affective states.

Experience-Related Findings in the Mid-Insula

The mid-insula is implicated in autonomic integration (Craig, 2011) suggesting that control of internal states may take a while to develop and continue to develop over years, for example through yoga experience. In support of this interpretation, an 8-week intervention including meditation and yoga, increased hippocampal GM volume but did not change insular GM, a region of interest in that study (Holzel et al., 2011). Perhaps related to our finding of increased left mid-insular GM volume as a function of yoga experience, is the finding of Lutz et al. (2013) and colleagues showing a reduced baseline activation in the left anterior insula during pain anticipation that correlated with lifetime meditation experience. Given that posterior-to-anterior processing in the insula is thought to mediate subjective sensations via homeostatic sensory integration (Craig, 2011), and given our finding that this group of yogis tolerated pain significantly longer than matched controls (Villemure et al., 2013), it seems reasonable to speculate that yogis could also show a reduced baseline left anterior insular activation during pain anticipation correlating with experience, perhaps mediated by increased insular volume found in the current study.

Experience-Related Findings in the OFC

Larger OFC GM volume could be related to better emotional regulation with increasing yoga experience (Kringelbach, 2005). OFC activation was involved in the reduction of pain unpleasantness ratings when novice mindfulness practitioners meditated while exposed to noxious stimulation (Zeidan et al., 2011) suggesting that this area is involved in emotion regulation stemming from a meditative practice. It is therefore possible that increasing yoga experience, which is a meditative practice, could result in increased OFC GM volume over time.

Experience-Related Findings in the Frontal Operculum

It is unclear why larger left frontal operculum volumes (BA 44) were found in the most experienced yogis since traditionally the function of BA 44, a part of Broca's area, is ascribed to language (see Friederici, 2011 for a review). However, Broca's area is also involved in non-language processing domains and has been suggested to generally support hierarchical sequence processing (Friederici, 2011). As such, increasing experience in a non-linguistic domain involving sequence processing (music) was previously reported to increase left Broca's area GM density (Sluming et al., 2002). Yoga practice requires sequencing movements and breath control exercises in a hierarchical fashion to create a practice where each element leads to the next, promoting a smooth transition toward an ultimate goal. Larger left BA 44 in the most experienced yogis might be related to this process since more experienced practitioners are more likely to rely on their own sequencing in their personal practice than on that of a third party, such as a teacher. In fact, most yoga practitioners in our study were also yoga teachers and the more experienced yogis devoted more time teaching yoga each week. It is therefore reasonable to presume that they were also more proficient in designing yoga sequences.

Experience-Related Findings in Middle Temporal Gyrus

Finally, more yoga experience was associated with larger GM volume in the right middle temporal gyrus (BA 21). A somewhat comparable region, although in the left hemisphere (peak *x, y, z* coordinates: −51, −31, −9; ours: 64, −31, −6), was found to correlate with meditation experience (Leung et al., 2013). A similar region (peak *x, y, z* coordinates: 54, −32, −7) was among a network of brain regions reported to monitor the transition from innocuous to painful sensation (Johnstone et al., 2012). Yoga practitioners usually closely monitor this transition in order to increase flexibility but avoid stretching to levels that would induce pain, which may signal potential damage to the body. It is, however, unclear why this neuroanatomical change would take years to occur. Alternatively, the temporal lobe has also been implicated in mystical experiences characterized by insights into the unity of all reality and a feeling of positive affect of peace and joy (Saver and Rabin, 1997). For example, a similar area within the right temporal lobe (BA 21) was one of the brain areas activated when Carmelite nuns reported being in a state of union with God (Beauregard and Paquette, 2006). We do not know whether the yogis tested in the present study had ever experienced similar insights deriving from their yoga practice. Therefore, such an explanation remains highly speculative. However, the ultimate goal of yoga as described in the *Yoga Sutras* of Patanjali is to experience such union or oneness – referred to as *Samadhi* in Sanskrit. In any case, acquiring insights into the unity of all reality is likely to require years of practice.

GM Volume Related to Weekly Practice

Short-term activity-dependent plasticity in the adult human brain is a known phenomenon and can occur very rapidly. These activity-dependent GM changes are accompanied by perceptual and/or performance changes, and usually regress shortly after the activity is terminated. For example, it was previously demonstrated that short-term but repeated presentation of painful stimuli over 8 days increases both pain thresholds and GM density in S1 cortex and that these changes recede after regular nociceptive input is discontinued (Teutsch et al., 2008). Similarly, short-term training for a specific visuo-motor skill results in transient spatially selective increase in GM volume reverting to original size shortly after cessation of training and regression of skill performance (Draganski et al., 2004). This suggests that even if certain brain areas can rapidly show volume changes in the face of exposure or training, continuous training might be necessary to maintain skill/performance/benefits and GM volume increase. This could imply that less practice would not sustain GM volume gains as well as more practice and is likely related to our findings that more time devoted to yoga practice weekly impacts some areas of the brain recruited during the practice, likely helping in the further development and maintenance of structural changes even in experienced practitioners. Indeed, we found evidence of practice-dependent brain alterations related to the number of hours devoted to yoga each week in the right S1/SPL, left hippocampus, midline precuneus/PCC, and right V1.

S1/SPL and Precuneus/PCC Volumetric GM Alterations Associated with Weekly Yoga Practice

Yoga involves interoceptive awareness and focused attention. During the practice of yoga postures, attention is consciously directed to the breath, body alignment and position, and emotional state. This might be related to alterations in S1 cortex, which contains a representational map of the entire body receiving increasing sensory input with increasing hours of weekly practice, as well as alterations in SPL, involved in the voluntary orienting of attention (Corbetta and Shulman, 2002), and precuneus/PCC, which belong to a network of midline structures thought to be crucial for the integration of self-referential stimuli in the emotional and autobiographical context (Northoff and Bermpohl, 2004; Holzel et al., 2011). Increasing gray matter (GM) volume in all these areas could reflect enhanced somatic awareness related to an increasing weekly amount of yoga practice. Rank ordering of variable importance using the multiple regression product measures, revealed that the practice of postures contributed more to the prediction of S1/SPL volume, while yoga-related meditation contributed more to the prediction of the volume of precuneus/PCC. This is in accordance with the nature of the processing taking place in those structures.

V1 GM Alterations Associated with Weekly Yoga Practice

Larger GM volume in V1 with increasing weekly practice may be related to some yogic practices involving visualization of objects or scenery, such as some meditation/relaxation techniques including *yoga nidra,* and some breath control exercises requiring visualizing the passage of air through the respiratory system or visualizing that the breath reaches different parts of the body. Indeed, V1 can be activated in neuroimaging studies of visual mental imagery (Kosslyn and Thompson, 2003). However, it must be noted that we did not specifically document the use of visualization practices in the current sample of subjects. It is nevertheless worth noting that V1 was the only brain structure whose volume correlated with the numbers of hours of weekly breath control practice. Furthermore, The beta coefficient related to breath control exercises was significant only for V1 and associated with a large structure coefficient indicating the number of hours of breath control exercises was a good predictor of V1 volume. The commonality analysis showed that the combination of meditation and breath control exercises accounted for almost half the variance in V1.

Hippocampal GM Alterations Associated with Weekly Yoga Practice

Spending more time doing yoga each week was associated with larger left hippocampal GM volume. Previous studies found that both hippocampi were activated in yoga teachers during *yoga nidra,* a relaxation/meditation technique (Lou et al., 1999) while the left hippocampus was activated during a Kundalini yoga meditation involving attending to the breath while silently repeating Sanskrit words (Lazar et al., 2000). Increased left hippocampal GM was also recently reported following an 8-week mindfulness-based stress reduction intervention including sitting meditation and yoga (Holzel et al., 2011) while significantly greater hippocampal GM volume/density have been repeatedly found in experienced meditators than controls either in the right (Holzel et al., 2008; Luders et al., 2009) or left hippocampus (Luders et al., 2013a,b) with hippocampal volume correlating with experience (Luders et al., 2013a). In older adults, greater aerobic fitness and cardiopulmonary function were also associated with increased hippocampal volume (Pereira et al., 2007; Erickson et al., 2009). Here, the product measure derived from the multiple regression analysis indicated that both the number of hours devoted to yoga postures and to yoga-related meditation were almost equally contributing to the prediction of the left hippocampal volume while the commonality analysis showed that nearly half of the explained variance was related to the combination of postures and meditation. A recent literature review has linked the hippocampus and the regulation of stress hormones (Goosens, 2011) and yoga has been shown to decrease stress and/or anxiety symptoms [for a review see Li and Goldsmith, 2012]. Importantly, a relationship between hippocampal volume and cortisol response to stressors has been reported in humans, with larger hippocampi associated with lower cortisol secretion in response to stressors (Pruessner et al., 2005). Additionally, Luders et al. (2013a), using refined cytoarchitectonic probabilistic maps of peri-hippocampal subsections, found that the effect of meditation on hippocampal volume were specific to the subiculum, a structure known to play a key role in stress regulation (Luders et al., 2013a).

Together these findings suggest that more is better when it comes to the frequency of yoga practice notably as far as somatosensation, attention, self-relevant processing, and stress regulation are concerned. This dose-response should be taken into account in eventual longitudinal studies evaluating the effects of yoga practice on regional brain volume changes.

Limitations

Our relatively small sample size may have prevented us from identifying subtler GM differences. Matching groups on the amount of exercise performed outside yoga may be viewed as a limitation given that postures may be considered a form of physical exercise and, as mentioned before, physical activity and cardiovascular function can impact brain structure. The global GM differences observed between groups could hypothetically be entirely attributed to this extra amount of physical activity. However, postures are an integral part of yoga practice and are more than a simple physical activity, as practitioners are trained to do them with mindful awareness. Further, it can be argued that a relatively small proportion of *asana*, notably "sun salutations," involve aerobic exercise that may improve cardiovascular function if a sufficient number of series are performed vigorously enough (i.e., at age-predicted 80% heart rate max; Mody, 2011). Finally, within our yoga group, only a proportion of the effects of weekly yoga practice on the brain were attributable to *asana* and this proportion varied depending on the brain region, with some regions being only modestly influenced by postures.

The use of a higher-resolution head coil (such as the recently developed 32-channel coil) might have permitted us to detect more subtle GM differences, though recent research (Streitburger et al., 2014) suggests that the MP-RAGE sequence used in the current study does not benefit significantly from the potential advantages of a 32-channel coil. Another limitation is that VBM does not allow us to determine what underlies the observed GM changes described here. GM changes could result from many causes, one likely explanation being synaptic changes such as increased spine density associated with synapse formation (Trachtenberg et al., 2002) and pre-synaptic neuronal remodeling (Lerch et al., 2011). This last study directly evaluated the mechanism of experience-dependent volumetric changes in a rodent model of maze learning and found that changes in VBM correlated with Gap-34 staining, a marker of neuronal process remodeling (Lerch et al., 2011). Although this study did not measure changes in dendritic spines, the axonal/presynaptic changes found are thought to occur in parallel with the formation and persistence of specific postsynaptic dendritic spines and associated synapses (reviewed in Fu and Zuo, 2011). Additionally, there is evidence to suggest that glial cell alterations also support structural neuroplasticity (Blumenfeld-Katzir et al., 2011; Johansen-Berg et al., 2012; Sagi et al., 2012).

Despite the cross-sectional nature of this study, the current findings (the correlations between GM volume of several brain areas and yoga experience and practice frequency, the relationship between different aspects of yoga practice and changes in different brain areas, and the possible evidence against age-related whole-brain GM decline in yogis) suggest that yoga practice contributes to the observed brain differences. However, we cannot totally exclude that our sample of yogis had fundamentally different brains to begin with, predisposing them to adopt yoga practice and/or persevering on that path. In fact, some of our results suggest that yoga practitioners might have started with smaller brain volumes in certain brain areas before reaching higher levels of experience. This was particularly evident for the brain areas correlating with the number of years of experience. For example, **Figure 3A** shows that increasing yoga experience is associated with increasing left OFC volume. It also shows that the average OFC volume of the matched control subjects was that of a yoga practitioner with approximately 10 years of experience. As previously mentioned, OFC is involved in emotional regulation and the left hemisphere is mostly related to positive affect. This opens the intriguing possibility that individuals with smaller left OFC might be drawn to yoga practice and, as their left OFC volume increases with yoga practice, and presumably as the benefits of having a larger OFC volume manifest, they continue to persevere on the yoga path. Interestingly, we reported in our previous manuscript that one of the most cited reasons to do yoga in this particular group of subjects was to improve mood (Villemure et al., 2013). However, this remains speculative and longitudinal studies are needed to determine how much of these observations are related to predisposing factors and how much are related to actual yoga practice.

Conclusion

In conclusion, regular practice of yoga may have neuroprotective effects against whole brain age-related GM decline. Additionally, our results suggest that more weekly regular yoga practice is associated with larger brain volume in areas involved in bodily representation, attention, self-relevant processing, visualization, and stress regulation. Distinct components of yoga practice (postures, breathing exercises, and meditation) or combination of these predicted GM volumes of these brain areas differently, in keeping with the nature of the processing taking place in those structures. Furthermore, certain brain changes continue to occur after several years of practice, as reflected by the link between increasing yoga experience and increasing brain volume in areas subserving autonomic integration, emotional processing and regulation, hierarchical sequential organization, and in a brain area implicated in either the monitoring of the transition between innocuous to painful sensation or in experiences characterized by insights into the unity of all reality and feelings of peace and joy. Most of these experience-related changes were located in the left hemisphere suggesting that increasing years of yoga practice progressively tunes the brain toward a parasympathetically driven mode and positive affective states. Together these findings provide a neural basis for some of the beneficial effects of yoga. Finally, the current study involved yoga practitioners who were otherwise typical North Americans. As such, if the observed structural brain variances are indeed related to yoga training, they should be within the reach of the average person and not reserved to a select few.

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frontiers in Human Neuroscience

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Greater widespread functional connectivity of the caudate in older adults who practice kripalu yoga and vipassana meditation than in controls

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There has been a growing interest in understanding how contemplative practices affect brain functional organization. However, most studies have restricted their exploration to predefined networks. Furthermore, scientific comparisons of different contemplative traditions are largely lacking. Here we explored differences in whole brain resting state functional connectivity between experienced yoga practitioners, experienced meditators, and matched controls. Analyses were repeated in an independent sample of experienced meditators and matched controls. Analyses utilizing Network-Based Statistics (Zalesky et al., 2010) revealed difference components for yoga practitioners > controls and meditators > controls in which the right caudate was a central node. Follow up analyses revealed that yoga practitioners and meditators had significantly greater degree centrality in the caudate than controls. This greater degree centrality was not driven by single connections but by greater connectivity between the caudate and numerous brain regions. Findings of greater caudate connectivity in meditators than in controls was replicated in an independent dataset. These findings suggest that yoga and meditation practitioners have stronger functional connectivity within basal ganglia cortico-thalamic feedback loops than non-practitioners. Although we could not provide evidence for its mechanistic role, this greater connectivity might be related to the often reported effects of meditation and yoga on behavioral flexibility, mental health, and well-being.

Keywords: caudate, functional connectivity, graph theory, degree centrality, yoga, mindfulness meditation, aging, basal ganglia-thalamocortical circuits

Introduction

There is a growing interest in the neural correlates of meditation practice. While initial studies focused on the meditative state or the effects of meditation on brain activation during a specific task, more recent studies also have investigated the effect of ongoing regular meditation experience on the resting state of the brain (Jang et al., 2010; Brewer et al., 2011;

Kilpatrick et al., 2011; Taylor et al., 2012). These studies have provided first insights in how meditation affects functional brain connectivity at rest. An important limitation of these studies is that they only investigate differences in connectivity between nodes of the default mode network (Buckner et al., 2008) without accounting for the complex network structure that these connections underpin. Recent models of the brain as a complex network has furthered the understanding of its resting state and provided robust methods to compare its properties amongst subjects based on graph theory. These methods refrain from comparing the fMRI signal at every voxel, thereby increasing the statistical power of group comparisons. Therefore this approach is particularly useful for studying the brain resting state between groups of healthy subjects, for which differences may be subtle.

Further, the above-mentioned studies focused only on practitioners of meditation. There is much theoretical debate about how various contemplative practices may be similar or different, both in terms of mechanisms and effects. There is a growing interest in understanding how different contemplative practices compare (Brewer et al., 2011). A study directly comparing different practices may therefore provide invaluable insights into the neural processes involved and provide concrete evidence as to how these practices differ, or not.

In a recent, *hypothesis driven* study, we addressed these issues, and investigated *global* resting state brain functional network properties of yoga- and meditation practitioners (Gard et al., 2014b). Here we use *explorative* methods on the same dataset to investigate *local* differences in the brain resting state functional networks of individuals with extensive meditation or yoga practice compared to demographically matched controls. Unlike previous studies, we use a data-driven approach to reliably identify the differences in networks between the groups across the entire brain, without limiting ourselves to any a priori sub-network or region and without the need of a specific hypothesis. To strengthen confidence in the main finding, we repeated analyses with a second, independent dataset of experienced meditators and controls. Results will be discussed in the light of recent research on the role of the basal ganglia.

Materials and Methods

Participants

The first study consisted of 47 participants: 16 yoga practitioners, 16 meditation practitioners, and 15 controls. The three groups were matched for age, sex, education, and handedness. Yoga practitioners were primarily trained in the Kripalu Yoga (Faulds, 2005) tradition and had an average of 13,534 (SD = 9,950) hours of yoga experience. Meditators were primarily trained in Vipassana (a.k.a. insight or mindfulness) meditation (Goldstein and Kornfield, 2001) and had an average of 7,458 h (SD = 5,734) of meditation experience. Controls had less than 4 yoga or meditation classes in the past year and less than 10 classes in their lifetime. See **Table 1** for the demographic characteristics of each group. Participants provided written informed consent and were compensated $100 for their time. The study was approved by the Partners Human Research Committee, Massachusetts General Hospital (protocol 2005P001392). Other data from these subjects has been published elsewhere (Gard et al., 2014b).

For the replication study we used data of a subset of individuals who participated in a previously published study (Lazar et al., 2005). Resting state BOLD data was available for 13 Vipassana meditation practitioners and 16 controls with little or no meditation experience (less than 4 classes in the past year and less than 10 classes in their lifetime). Meditators had an average experience of 4,831 (SD = 3,738) hours. See **Table 2** for the demographic characteristics of each group. Participants provided written informed consent and were compensated $100 for their time. The study was approved by the Partners Human Research Committee, Massachusetts General Hospital (protocol 2000p-001392).

Image Acquisition

For the original study data was collected on a Siemens 1.5 Tesla Avanto MRI scanner (Erlagen, Germany) at the Martinos Center for Biomedical Imaging. Structural images were acquired using a T1-weighted magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence (128 sagittal slices, slice thickness = 1.33 mm, TR = 2.73 s, TE = 3.39 ms, flip angle = 7°, field of view = 256 mm × 256 mm, matrix = 192 mm × 192 mm). A 5 min functional resting state scan was acquired using a gradient echo T2*-weighted sequence (TR = 2.5 s, TE = 40 ms, FA = 90°, field of view = 320 mm × 320 mm, matrix = 64 mm × 64 mm). Twenty five sagittal slices with 1 mm gap (voxel size: 3.13 mm × 3.13 mm × 5 mm) were acquired inter-leaved.

For the replication study data was collected on a Siemens 1.5 Tesla Sonata MRI scanner (Erlagen, Germany) at the Martinos Center for Biomedical Imaging. Structural images were acquired using a T1-weighted magnetization prepared rapid acquisition gradient echo (MPRAGE) sequence (128 sagittal slices,

TABLE 1 | Comparison of demographic variables between controls, yoga practitioners, and meditators for the original dataset.

	Controls		Yoga practitioners		Meditators *M* / %		ANOVA / χ^2-test		
	M /%	SD	*M* /%	SD	*M* /%	SD	*F* / χ^2	*df*	*p*
Age (years)	52.93	9.84	49.38	7.79	54.06	8.15	1.29	2, 44	0.286
Education (years)	17.27	1.98	17.31	2.41	18.44	2.58	1.26	2, 44	0.293
Gender (% female)	60%		69%		63%		0.28	2	0.871
Handedness (% right)	87%		88%		88%		0.01	2	0.997

TABLE 2 | Comparison of demographic variables between controls, and meditators for the replication dataset.

	Controls		Meditators *M* / %		*t*-test / χ^2-test		
	M /%	SD	*M* /%	SD	t / χ^2	*df*	*p*
Age (years)	36.00	7.67	38.15	7.85	0.74	27	0.463
Education (years)	17.13	1.77	17.54	1.85	0.59	26	0.559
Gender (% female)	44%		31%		0.51	1	0.474
Handedness (% right)	100%		100%				

slice thickness = 1.33 mm, TR = 2.73 s, TE = 3.39 ms, flip angle = 7°, field of view = 256 mm × 256 mm, matrix = 192 mm × 192 mm). A 6.7 min functional resting state scan was acquired using a gradient echo T2*-weighted sequence (TR = 4 s, TE = 40 ms, FA = 90°, field of view = 320 × 320 mm, matrix = 64 × 64 mm). Twenty-five sagittal slices with 1 mm gap (voxel size: 3.13 mm × 3.13 mm × 5 mm) were acquired interleaved. Participants of both the original and the replication study were instructed not to meditate during the resting state scan.

Analysis

Demographics

To test if groups were successfully demographically matched for age and education, ANOVAs and independent sample *t*-tests (two-tailed) were conducted for the original and the replication study, respectively. To evaluate comparability on gender and handedness, χ^2-tests were conducted for both studies.

Data Preprocessing

For both studies resting state data were slice time corrected, realigned, coregistered to individual T1-weighted images, normalized, and spatially smoothed with at 5 mm kernel using SPM8[1] (Wellcome Department of Cognitive Neurology, London, UK). Next, in the original study the first eight volumes of the functional time series were discarded to allow for stabilization of the MR signal. The remaining 112 volumes were further preprocessed using the Connectivity toolbox[2] (Whitfield-Gabrieli et al., 2010). In the replication study the first five volumes were discarded and the remaining 95 were further processed in the same way as the data from the original study. Mean white matter signal, mean CSF signal, six motion parameters, and the first order motion derivative were regressed out of the data. Finally, the residual time series were band-pass filtered with a window of 0.008–0.09 Hz.

Anatomical Parcellation and Time Series Extraction

Resting state scans were parcellated into 116 regions of interest (ROIs; 90 cortical and subcortical, and 26 cerebellar) using the Automated Anatomical Labeling (AAL; Tzourio-Mazoyer et al., 2002) template in the Wake Forest University (WFU) Pickatlas version 2.5 (Maldjian et al., 2003). For each ROI, the average (of all voxels in the ROI) preprocessed time-series was extracted, resulting in a 116 (ROIs) × 112 (volumes) time-series matrix for each subject. Time-series extraction was done with the Connectivity toolbox[3] (Whitfield-Gabrieli et al., 2010).

Network Analysis

Networks are defined as a set of nodes connected by links. In the context of functional network analysis, the nodes are each of the 116 regions of interest and the links represent the strength of the connections between them.

Anatomical parcellation and time series extraction result in a time-series matrix for each subject. The correlations between each pair of time series of each such correlation matrix were computed, resulting in a 116 × 116 correlation matrix. The elements of this matrix are therefore real numbers between −1 and 1. All negative entries were set to zero so that all elements belong to [0,1], which is a necessary step to obtain a network with positive weights (Schwarz and McGonigle, 2011).

These matrices essentially define networks wherein the (i,j) entry of the matrix is the strength of the connection between the i-th and j-th ROI. These networks are weighted (because the connections can have any value between zero and one) and undirected [because the (i,j) entry of the matrix equal the (j,i) entry]. Our choice of using weighted networks instead of unweighted ones (obtained by further binarizing positive weights) is motivated by (Wang et al., 2011) showing that analysis of weighted networks is more reliable and (Barrat et al., 2004) showing that binarization results in a loss of valuable information. The networks were then analyzed using NetworkX (Hagberg et al., 2008).

Network-Based Statistics

One-to-one comparisons between groups for each connections in the network would result in many comparisons to be made. These comparisons may lack statistical power due to the need to correct for multiple comparisons. To explore differences in resting state brain functional connectivity between yoga practitioners, meditators, and controls, while considering the entire brain network, we therefore employed Network-Based Statistics (NBS) which detects clusters of connections (instead of individual connections) that significantly differ between group. NBS is a solution to the multiple comparison problem. NBS assumes that edges contributing to population differences tend to appear in connected components (Zalesky et al., 2010). Introducing this assumption decreases the number of comparisons and unveils clusters of edges that significantly differ between the groups.

More specifically, we used the NBS method for the comparisons yoga practitioners > controls, meditators > controls, and

[1] www.fil.ion.ucl.ac.uk/spm/

[2] http://www.nitrc.org/projects/conn

[3] http://www.nitrc.org/projects/conn

yoga practitioners versus meditators (two-sided test). For the comparisons involving controls we used one-sided tests, based on previous studies that found greater resting stage connectivity in meditators compared to controls (Brewer et al., 2011). Much like cluster-based statistics, NBS requires a threshold on the t-statistics (or equivalently on the p-value) of individual edge differences. Connected components are subsequently defined in the binary network of supra-threshold edges. To explore spatially small, hence interpretable, subnetworks, we used a relatively severe initial threshold of $p < 0.00005$.

Degree Centrality

Network-based statistics limits the number of comparisons by automatically and reliably identifying subnetworks of interests. To further investigate the central role that the caudate (central node of the detected subnetworks) plays in the functional networks for yoga practitioners > controls and meditators > controls, degree centrality of the caudate was computed for each subject (Eq. 1). Degree centrality was chosen as it is conceptually the simplest measure of nodal importance in a network. Degree centrality is defined as:

$$C_D(v) = \frac{\deg(v)}{n-1} \tag{1}$$

where deg(v) is the weighted degree of the node v (i.e., the sum of the strengths of its connections) and n is the total number of nodes in the network. A larger degree centrality therefore implies that the node is more connected to the rest of the network.

We compared the degree centrality of controls, meditators, and yoga practitioners for the left and right caudate nuclei. Since the assumption of homogeneity of variances was not met, we used a Welch's test to assess the equality of means in the population. The test was followed up by independent two-tailed t-tests comparing yoga practitioners, meditators, and controls pairwise. To validate the findings from these analyses, we tested the hypothesis that meditators have greater degree centrality than controls (independent samples t-test, one-tailed) in an independent dataset of 13 meditators and 16 controls.

Individual Edges

To follow up the finding of greater degree centrality of the caudate in yoga practitioners and meditators vs. controls, connectivity between the caudate and each of the 115 other nodes in the network was compared between yoga practitioners and controls and meditators and controls. To do so, correlation coefficients were Fisher-transformed (Eq. 2) to obtain normally distributed values which were used for the second-level node-wise analysis.

$$z = \frac{1}{2}\ln\frac{1+r}{1-r} = \operatorname{arctanh}(r), \tag{2}$$

where r represents the correlation coefficient value.

Then, independent samples t-tests (two-tailed) were calculated for each edge for yoga practitioners vs. controls, and meditators vs. controls. Correction for multiple comparisons was done using the False Discovery Rate (FDR) <0.5; Genovese et al., 2002). Fisher transformation, and the node-wise analysis was done with the Connectivity toolbox[4] (Whitfield-Gabrieli et al., 2010). Again, to validate the findings from this analysis we repeated the above analyses on an independent dataset of 13 meditators and 16 controls.

Cognitive and Practice Assessment

Due to the role of the caudate in aging and cognitive functioning, the relation between degree centrality in the left and right caudates and age and fluid intelligence was explored. This was done by calculating Pearson product moment correlations within groups and over the merged groups. Fluid intelligence was measured with the odd items of the Raven's Advanced Progressive Matrices (APM; Raven et al., 1998; Raven, 2000). In addition, the relationship between amount of yoga- or meditation practice and degree centrality in the left and right caudates was explored in the yoga- and meditation groups, using Pearson product moment correlations. Amount of lifetime practice was based on participant's self-reported estimates.

Results

To test the success of participant matching in both the original as well as in the replication data set, ANOVAs, t-tests and χ^2-test were conducted. There were no significant differences in age, education, gender, and handedness between yoga practitioners, meditators, and controls in the original data set (**Table 1**). In the replication data set there also were no differences on these variables between meditators and controls (**Table 2**).

Network-Based Statistics

To compare whole brain resting state networks of yoga practitioners, meditators, and controls, the (NBS; Zalesky et al., 2010), a novel approach to correct edgewise connectivity for multiple comparisons, was used. At the stringent initial p-threshold of $p < 0.00005$, this approach revealed a significant ($p = 0.031$) difference component for the comparison yoga practitioners > controls. This component was comprised of three nodes and two edges, with the right caudate serving as the central node, connected to the left parahippocampal gyrus and the left inferior temporal gyrus (**Figure 1A**). The comparisons meditators > controls and yoga practitioners versus meditators did not reveal significant difference components. Although not significant ($p = 0.176$), it is striking to note that the largest difference component for meditators > controls was comprised of the same two connected nodes, namely the right caudate and the left parahippocampal gyrus as in the difference network for yoga practitioners > controls (**Figure 1B**).

Degree Centrality Caudate

To further investigate the central role of the caudate in the identified components, we calculated the degree centrality of the right and left caudate for each participant's weighted network and compared it between groups. Welch's test of equality of means, which is an alternative to ANOVA when the assumption of homogeneity

[4]http://www.nitrc.org/projects/conn

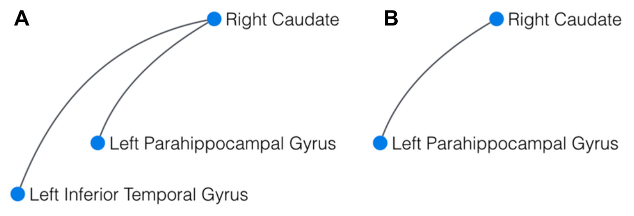

FIGURE 1 | Result of the network-based statistics (NBS). (A) In yoga practitioners vs. controls, NBS revealed a significant cluster of three interconnected components, centered around the right caudate. **(B)** In meditators vs controls, the largest component detected by NBS also comprised the right caudate and the left parahippocampal gyrus.

of variances is not met (Welch, 1951), revealed that the mean degree centrality was different for yoga practitioners, meditators, and controls in the right [$F(2,24.576) = 14.587, p < 0.001$] and in the left caudate [$F(2,23.785) = 5.867, p = 0.008$]. *Post hoc* independent samples t-tests (two-tailed) revealed that this effect in the left caudate was driven by greater weighted degree in yoga practitioners [$M = 0.132$, SD $= 0.088$; $t(18.390) = 2.171, p = 0.038$] and meditators [$M = 0.148$, SD $= 0.088$; $t(19.362) = 2.801, p = 0.009$] than in controls ($M = 0.081$, SD $= 0.029$; **Figure 2A**). There was no significant difference between yoga practitioners and meditators [$t(30) = 0.490, p = 0.628$]. The effect in the right caudate also was driven by greater weighted degree in yoga practitioners [$M = 0.153$, SD $= 0.072$; $t(19.318) = 3.472, p = 0.003$] and meditators [$M = 0.176$, SD $= 0.073$; $t(19.224) = 4.641, p < 0.001$] than in controls ($M = 0.086$, SD $= 0.027$; **Figure 2B**). There was no significant difference between yoga practitioners and meditators [$t(30) = 0.916, p = 0.367$].

In the collapsed sample degree centrality of the left and right caudates were not significantly correlated with age [$r(45) = 0.033$, $p = 0.823$ and $r(45) = -0.64$, $p = 0.671$, respectively] or fluid intelligence [$r(45) = 0.130$, $p = 0.385$, and $r(45) = 0.043$, $p = 0.776$, respectively]. Also in controls degree centrality of the left and right caudates were not significantly correlated with age [$r(13) = -0.089$, $p = 0.753$, and $r(13) = -0.097$, $p = 0.731$, respectively] or fluid intelligence [$r(13) = 0.057$, $p = 0.839$, and $r(13) = -0.050$, $p = 0.861$, respectively]. Similarly in meditators degree centrality of the left and right caudates were not significantly correlated with age [$r(14) = -0.202$, $p = 0.453$, and $r(14) = -0.248$, $p = 0.354$, respectively], fluid intelligence [$r(14) = 0.063$, $p = 0.817$, and $r(14) = 0.183$, $p = 0.499$, respectively], or meditation practice [$r(11) = -0.051$, $p = 0.868$, and $r(11) = -0.279$, $p = 0.355$, respectively]. In yoga practitioners degree centrality of the left and right caudates were also not significantly correlated with age [$r(14) = 0.070$, $p = 0.798$, and $r(14) = 0.345$, $p = 0.191$, respectively], fluid intelligence [$r(14) = -0.353$, $p = 0.181$, and $r(14) = -0.314$, $p = 0.236$, respectively], or yoga practice [$r(11) = 0.292$, $p = 0.291$, and $r(11) = 0.418$, $p = 0.121$, respectively].

These findings were replicated in an independent dataset of 13 meditators and 16 controls. Meditators ($M = 0.130$, SD $= 0.067$) had significantly greater degree centrality in the left caudate than controls [$M = 0.065$, SD $= 0.028$; $t(15.269) = 3.238$, $p = 0.003$; **Figure 2C**]. In the right caudate meditators ($M = 1.463$, SD $= 0.089$) also had greater degree centrality than controls [$M = 0.090$, SD $= 0.049$; $t(17.746) = 2.021$, $p = 0.028$; **Figure 2D**]. Degree centrality in the left and right caudates were not significantly correlated with age in meditators, [$r(14) = -0.018, p = 0.954$, and $r(14) = 0.102, p = 0.741$, respectively], controls [$r(14) = 0.220$, $p = 0.414$, and $r(14) = -0.056$, $p = 0.837$, respectively], or in the collapsed sample [$r(27) = 0.126$, $p = 0.516$, and $r(27) = 0.088$, $p = 0.651$, respectively]. Amount of meditation practice was significantly correlated with degree centrality in left [$r(11) = -0.604$, $p = 0.029$] but not right [$r(11) = 0.124, p = 0.687$] caudate.

Individual Edges

To find out by what edges the greater centrality in yoga practitioners and meditators as compared to controls was driven, the average connectivity between the caudate and all 115 other brain regions was compared pairwise between yoga practitioners, meditators and controls. Yoga practitioners and meditators had stronger connectivity to a large number of brain regions as compared to controls, while there were no differences between yoga practitioners and meditators (**Figures 3A–D,G**, Tables S1–S2). The finding of greater connectivity between the caudate and a large number of brain regions in meditators than in controls was replicated in the independent dataset (**Figures 3E–G**, Table S3).

Discussion

Here we explored differences in resting state functional networks between yoga practitioners, meditators, and controls. Our data revealed that the caudate was a hub in the difference network (i.e., the network whose edges represent the differences between the groups) between yoga practitioners and controls. Not only was the caudate a hub in the difference network, yoga practitioners and meditators also had greater degree centrality in the caudate than controls. Further *post hoc* analyses revealed this greater degree centrality was not driven by a specific connection but rather by widespread stronger connectivity between the caudate and multiple regions across the rest of the brain.

Similarities between Yoga and Mindfulness Meditation

This finding of widespread stronger connectivity of the caudate in both yoga practitioners and meditators is consistent with overlapping theoretical mechanisms involved in both practices. Both Kripalu Yoga and Vipassana theoretically and empirically foster mindfulness, thereby sharing a key aspect (Faulds, 2005; Chiesa, 2010; Gard et al., 2012a; Perelman et al., 2012). This overlap between the practices might also be the reason why we did not find significant differences in global (Gard et al., 2014b) and local (this study) resting state brain networks between yoga practitioners and meditators. With a larger sample size it might be possible to identify more subtle differences in resting state network organization between yoga practitioners and meditators. It will also be

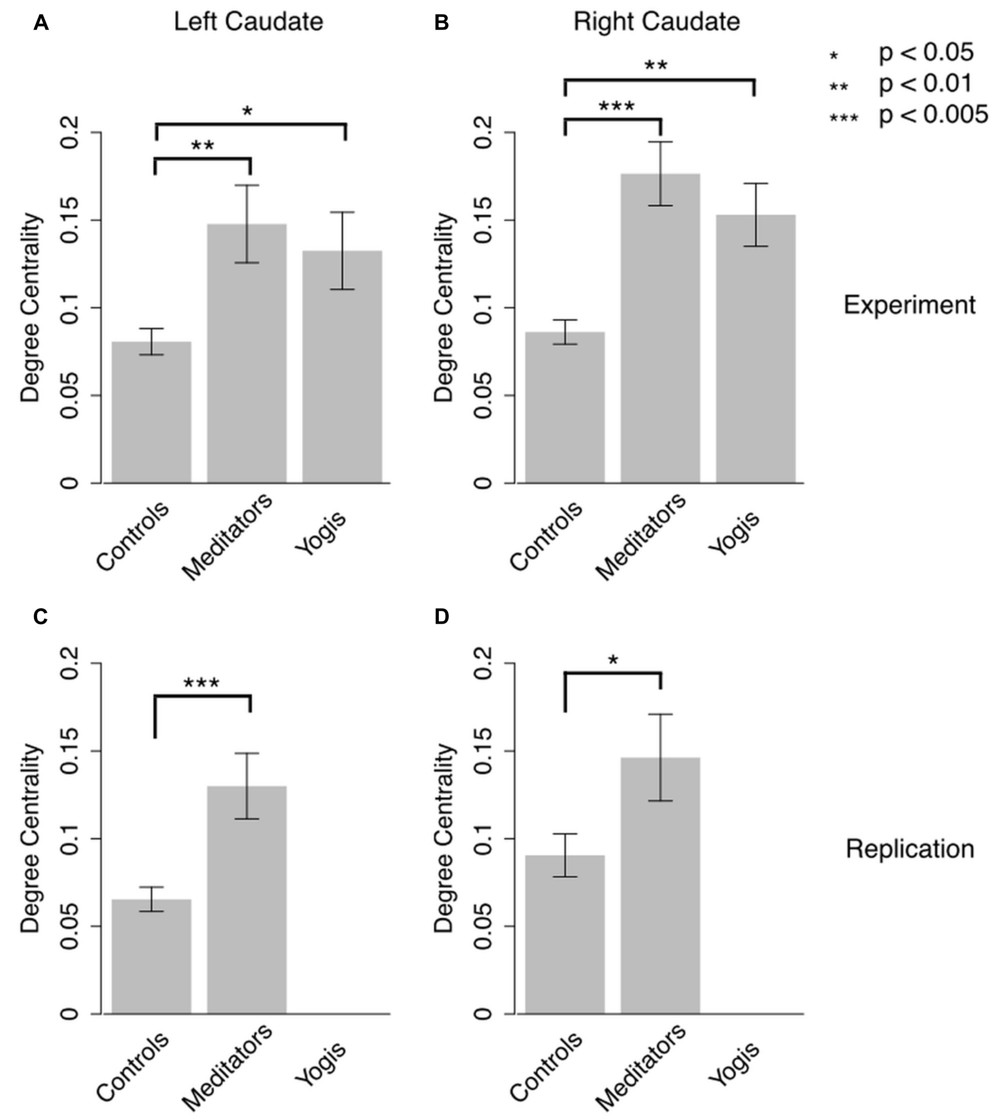

FIGURE 2 | Degree centrality in left and right caudate in the original experiment (A,B) and in the replication study (C,D). Error bars represent SE of the mean. *P*-values are based on independent samples *t*-tests.

interesting to test contemplative traditions that do not emphasize mindfulness.

The Caudate Findings in Yoga and Meditation

This is, to our knowledge, the first study revealing greater resting state functional connectivity between the caudate and a variety of brain regions in experienced yoga practitioners and meditators as compared to controls. Our finding of greater degree centrality in the caudate of meditators is particularly strong as it was replicated in an independent sample, collected at a different time, on a different scanner and with different scanning parameters. Remarkably, despite these technological differences, not only the statistical significance of the differences but also the magnitude of these differences were replicated (**Figure 2**).

The correlation between degree centrality in the left caudate and amount of meditation practice in the replication sample suggests that functional connectivity of the caudate is related to meditation experience. The negative direction of this relation in combination with greater caudate connectivity in meditators than in controls resembles the pattern of an inverted u-shape that has previously been reported in meditators with regard to brain activity (e.g., Brefczynski-Lewis et al., 2007; Gard et al., 2012b). However, in the original sample no relation between amount of practice and degree centrality of the caudate was found. This might be the result of a small sample size and the fact that imprecise practice estimates, as participants indicated that it was difficult to recall their lifetime practice. Structural findings.

Although not much is known about the role of the caudate in meditation, this structure has been reported in several

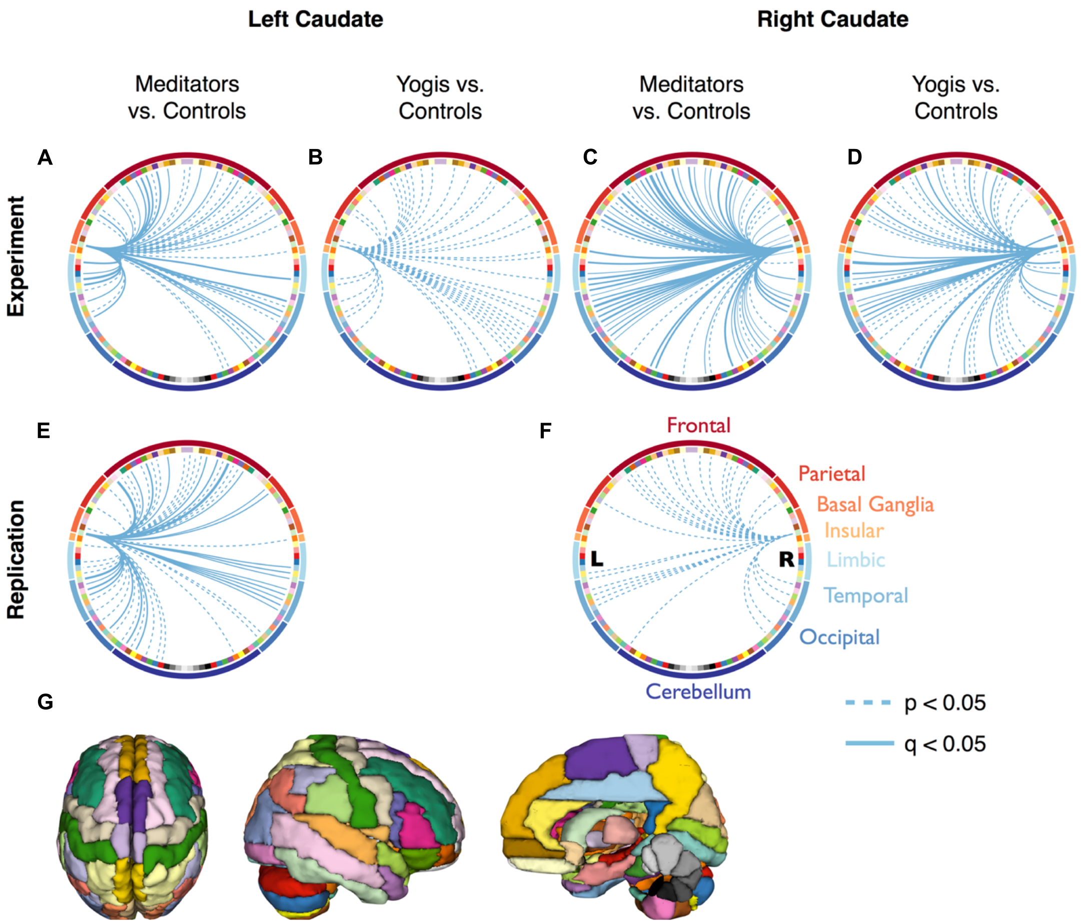

FIGURE 3 | Connectivity between the caudate and all 115 other regions of the Automated Anatomical Labeling (AAL) atlas. Continuous lines represent significantly stronger connections compared to controls, after False Discovery Rate (FDR) correction ($q < 0.05$). Dashed lines represent significantly stronger connections without FDR correction ($p < 0.05$). **(A–D)** are based on the original dataset, while **(E,F)** are based on the replication data-set. The colors of the nodes in **(A–F)** correspond to the parcellation in **(G)** and are clustered according to the main brain region they belong to (frontal, parietal, limbic, temporal, and occipital lobes, and basal ganglia, insular cortex, and cerebellum). Significant connections and their *p*-values are listed in Supplementary Tables S1–S3.

meditation-related brain imaging studies. Structural brain imaging studies revealed increased gray matter volume/density in the caudate after completion of 8-week mindfulness-based interventions (Farb et al., 2013; Pickut et al., 2013), while dispositional mindfulness in non-meditators has been reported to be negatively correlated with caudate volume (Taren et al., 2013).

Functional Activation Findings

Functional studies have revealed increased activity in this region during the state of meditation. Lazar et al. (2000) for example found increased caudate activation during kundalini silent mantra meditation as compared to a silent random word generation task in experienced kundalini meditation practitioners. Dickenson et al. (2013) reported increased caudate activity in novice mediators during mindful breath awareness as compared to mind wandering. Another study that assessed activity during different phases in the interplay between mindful awareness and mind wandering in moderately experienced meditators revealed increased caudate activity during the attention shifting phase, when attention was shifted to the breath, as compared to mind wandering phase (Hasenkamp et al., 2012). Brefczynski-Lewis et al. (2007) also investigated different phases of the meditation process but in Tibetan Buddhist meditators with different levels of experience. They reported increased caudate activity only during the startup phase (first 10 s) of a concentrative meditation in the most experienced meditators (>37,000 h experience), while the less experienced long term meditators (10,000–24,000 h) also had increased caudate activity during the continuation phase of the meditation session. Another study that included a mix of Tibetan Buddhist and Zen meditators reported increased caudate activation during continuous meditation as compared to rest, although the analysis was not corrected for multiple comparisons (Baerentsen et al., 2009). The involvement of the caudate in the meditative state as compared to rest has further been confirmed by a meta analysis that included studies with a wide variety of meditation practices (Sperduti et al., 2012).

Despite clear differences on the surface, different meditation techniques seem to have some overlap in their neural basis, including in the caudate. However, one study investigating experienced Kria Yoga practitioners reported decreased activation of caudate during meditation (guided imagery) as compared to rest (Lou et al., 1999). This discrepancy might be due to that specific meditation practice, or to the fact that just before the experiment in the scanner started, participants had practiced an intense form of concentrative meditation for 2 h. Methodological differences between this early and the more recent studies may be another reason.

Increased caudate activity has also been reported at rest in novices after completing a short integrative body-mind meditation training (Tang et al., 2009). Furthermore, a sample of experienced meditators from a variety of traditions, including Tibetan Buddhist meditators ,and Franciscan nuns, have been shown to have greater caudate activity at rest than matched controls (Newberg et al., 2010).

Functional Connectivity Findings

The state of meditation has also been investigated in terms of brain connectivity. Baerentsen et al. (2009) performed Independent Component Analysis (ICAs) on the fMRI time-series during sustained meditation. This analysis revealed a number of components including one large component comprising the caudate, the lateral prefrontal cortex, the precentral gyrus, the insula, the temporal gyrus, the parahippocampal gyrus, the fusiform gyrus, the ligual gyrus, and the cerebellum. Our findings are aligned with this finding of a meditation-related network that involves the caudate, alongside frontal, and temporal brain regions. We extend the finding by revealing this network in both meditators and yoga practitioners, at rest, and by revealing the central role of the caudate in this network.

Basal Ganglia-Thalamocortical Loops

Most studies so far have only reported meditation-related caudate activity as a side finding and have not attempted to interpret it extensively. However, the role of the caudate in meditation has been discussed in a number of theoretical accounts. In these theories the caudate is discussed as a key component of the basal ganglia-thalamocortical circuits. These segregated circuits originate in functionally related cortical regions that send excitatory glutamatergic projections to specific parts of the striatum, which then send converging projections to the pallidus and substantia nigra through a direct net-inhibitory and an indirect net-excitatory pathway. Both pathways to the basal ganglia output regions are mostly GABAergic and are modulated by dopaminergic projections from the midbrain, resulting in net inhibition of the neurons in the output regions. The latter have GABAeric projections to specific thalamic nuclei which project back (glutamatergic) to the main prefrontal area that fed the loop and after which the loop is named. In three out of the five known loops, the oculomotor-, dorsolateral prefrontal-, and lateral orbitofrontal loops, the caudate is the central striatal component (Alexander et al., 1986; Alexander and Crutcher, 1990). In the oculomotor loop the caudate receives input from the frontal eyefields, the dorsolateral prefrontal cortex, and the posterior parietal cortex, and in the dorsolateral prefrontal loop from the posterior parietal cortex and the arcuate premotor area. In the lateral orbitofrontal loop it receives input from the superior and inferior temporal gyrus and from the anterior cingulate cortex (Alexander et al., 1986).

These frontal–subcortical loops have been related to a variety of human behaviors, including alterations in emotion and cognition as a result of lesions (Cummings, 1993). As Graybiel (2000) noted "Under conditions of circuit dysfunction, at one extreme excessive and repetitive actions or thoughts could result, and at the other extreme poverty of movement or thought could be the result." A recent meta-analysis has related caudate functional connectivity in particular to cognition, emotion, action, and perception (Robinson et al., 2012).

With its broad converging cortical input, its gating function on the thalamus, and its modulation by the dopaminergic reward system, the basal ganglia are implicated in reinforcement learning: learning to take actions that maximize reward (Braunlich and Seger, 2013). Two types of reinforcement learning can be distinguished: model-based or goal-directed and model-free or habitual learning. The former involves value based and contingency learning and results in behavioral flexibility. The latter involves simple stimulus response learning and although low in computational cost it is not adaptive in changing environments (Schwabe and Wolf, 2011; Doll et al., 2012; Braunlich and Seger, 2013). While both types of learning utilize dopamine mediated reward prediction error signaling from the ventral tegmental area and the substantia nigra (Schultz et al., 1997), goal directed learning is mediated by the caudate and habitual learning by the putamen (Braunlich and Seger, 2013). Indeed, a recent study revealed that flexible goal-directed behavior was predicted by white matter structural connectivity between caudate and ventromedial prefrontal cortex while non-adaptive habitual behavior was predicted by connectivity between the putamen and the premotor cortex (de Wit et al., 2012). This finding combined with our finding of greater widespread caudate connectivity in yoga practitioners and meditators might suggest that the positive association between mindfulness and cognitive and behavioral flexibility (Carmody et al., 2009; Anicha et al., 2012) is mediated by connectivity between caudate and prefrontal cortex. Interestingly, stress which can be reduced through meditation and yoga (Carmody and Baer, 2008; Gard et al., 2012a), has been shown to result in a shift from goal-directed to habitual behavior (Schwabe and Wolf, 2011).

Theoretical Models of Yoga and Meditation

Some theoretical models of meditation and yoga incorporate basal ganglia–thalamocortical circuits. In the model of Vago and Silbersweig (2012) for example, these loops are closely related to the experiential enactive self (EES) network, one of four networks that they hypothesize to underlie self-awareness, self-regulation, and self-transcendence through mindfulness. The EES refers to a non-conscious sensory-affective-motor learning network that Vago and Silbersweig (2012) hypothesized to support attention regulation and awareness of sensory and mental activity. In a more recent paper, Vago (2014) explicitly extends this view to habits of minds. Similarly Gard et al. (2014a) have proposed that yoga practice also involves basal ganglia cortico-thalamic circuits that are involved in extinction learning to unlearn old, maladaptive behavioral patterns, and to establish new, adaptive ones.

Travis and Wallace (1999) proposed that the state of meditation is initiated by a "neural switch" network involving frontal brain regions and is further maintained by a "maintenance" network that involves basal ganglia cortico-thalamic feedback loops. Similarly Newberg and Iversen (2003) in their neurochemical model of meditation proposed that meditation is initiated by frontal brain regions and maintained by basal ganglia cortico-thalamic feedback loops. The involvement of these frontal-subcortical loops in this model is supported by the finding of increased dopamine release in the striatum during the yoga nidra meditation (Kjaer et al., 2002) and increased GABA levels in the thalamus after yoga practice (Streeter et al., 2007, 2010). However, in contrast to these models, a recent fMRI study (Baerentsen et al., 2009) did not find evidence for the frontal involvement but rather increased brain activity in the putamen at the onset of meditation. During sustained meditation, increased activation in the caudate was reported.

Based on these findings, the previously proposed models and their own meta-analysis, Sperduti et al. (2012) proposed a three component model for the state of meditation comprising an "interference control system," a "thoughts monitoring system," and a "self monitoring system." It is the interference control system that would support both the switching to and the maintenance of the meditative state through involvement of the putamen and the caudate as part of a basal ganglia cortico-thalamic feedback system. Sperduti et al. (2012) note that their model is based on increased brain activation during meditation as compared to baseline and suggest that it should be further validated with other methods including functional connectivity.

The fact that greater connectivity was not driven by single strong connections but by wide-spread connections including those to frontal, temporal and parietal regions, further suggests that yoga practitioners and meditators have more efficient basal ganglia cortico-thalamic feedback loops than controls. This enhanced basal ganglia cortico-thalamic feedback loop functioning even during a state of rest might be the result of repeated involvement of these loops during the state of meditation as proposed in the models of Travis and Wallace (1999), Newberg and Iversen (2003), Sperduti et al. (2012), Vago and Silbersweig (2012), and Gard et al. (2014a). This lasting change in basal ganglia cortico-thalamic feedback loops might be of clinical relevance as disturbances in these loops have been associated with mental health disorders, e.g., autism (Turner et al., 2006), obsessive compulsive disorder (Harrison et al., 2009), schizophrenia (Salvador et al., 2010; Simpson et al., 2010), and depression (Bluhm et al., 2009). This combined with our finding of increased connectivity between caudate and several brain regions, and the fact that mindfulness based interventions have been shown to improve mental health (Grossman et al., 2004), leads to the hypothesis that improved mental health due to mindfulness may be mediated in part by connectivity in caudate.

Aging, Cognition, and Caudate Connectivity

Normal aging and mild cognitive impairment are also both associated with decreased caudate connectivity (Klostermann et al., 2012; Morbelli et al., 2012; Podell et al., 2012; Agosta et al., 2013, but see Tomasi and Volkow, 2012), and caudate dopamine D1 receptor density (Rieckmann et al., 2011). Although we did not find a significant correlation between age and degree centrality in the caudate in the current samples, the greater degree centrality in caudate in yoga and meditation practitioners may be the result of decreased age-related decline rather than an increased caudate connectivity due to practice. Interestingly, studies have shown that the greater caudate-frontal connectivity in younger subjects is associated with better working memory performance (Klostermann et al., 2012; Podell et al., 2012) and that the shape and volume of the striatum are related to intelligence (Burgaleta et al., 2014; MacDonald et al., 2014). Based on these findings, combined with our previous finding in the current sample that age-related decline in fluid intelligence is offset in yoga and meditation practitioners (Gard et al., 2014b), it might be hypothesized that decreased age-related decline in fluid intelligence in yoga and meditation practitioners is mediated in part by increased caudate connectivity. However, we did not find a significant correlation between fluid intelligence and degree centrality in caudate, possibly due to power limitations.

Limitations

This study has several limitations. The design is cross sectional so no inference about the causality of the greater caudate connectivity can be made. Furthermore, although instructed to rest and not to meditate, there is no objective way to verify that participants were not actively meditating during the resting state scan. Lastly, as participants in the first sample as well as half of the participants in the replication study are of middle age, it is not clear if greater caudate connectivity is the result of a meditation-related increase or an offset of age-related decline. This limitation of potential age-related effects is a problem in many studies with experienced yoga and meditation practitioners as many practitioners with extensive practice tend to be older.

Conclusion

In summary, we have demonstrated in two independent datasets that yoga practitioners and meditators have greater degree centrality in the caudate than matched controls. *Post hoc* analyses of both datasets revealed that the greater connectivity of the caudate was driven by wide spread connectivity to most of the cerebrum, including frontal, temporal, and parietal brain regions.

These findings provide evidence for the previously hypothesized involvement of basal ganglia cortico-thalamic feedback loops in meditation (Sperduti et al., 2012) and yoga (Gard et al., 2014a). At the same time they extend these hypotheses by revealing stronger caudate connectivity not only in meditators but also in yoga practitioners. There have been relatively few neuroimaging studies of yoga practitioners and no studies directly comparing yoga and meditation practitioners, thus these data provide important information suggesting that different contemplative practices may have some similarities at the neural level. The current study was relatively small and was cross-sectional in design, so further studies with larger sample sizes and longitudinal designs are necessary to reveal the more subtle differences between the two. Our findings also extend previous hypotheses involvement of basal ganglia cortico-thalamic feedback loops during a state of meditation by providing support for increased connectivity in these loops during rest. This increased connectivity in these loops could be a potential mechanism accounting for improved behavioral flexibility, mental health, and well-being that is associated with yoga and meditation. Further research is required to test this hypothesis.

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Supplementary Material

The Supplementary Material for this article can be found online at: http://www.frontiersin.org/journal/10.3389/fnhum.2015.00137/abstract

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Processing of proprioceptive and vestibular body signals and self-transcendence in Ashtanga yoga practitioners

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In the rod and frame test (RFT), participants are asked to set a tilted visual linear marker (i.e., a rod), embedded in a square, to the subjective vertical, irrespective of the surrounding frame. People not influenced by the frame tilt are defined as field-independent, while people biased in their rod verticality perception are field-dependent. Performing RFT requires the integration of proprioceptive, vestibular and visual signals with the latter accounting for field-dependency. Studies indicate that motor experts in body-related, balance-improving disciplines tend to be field-independent, i.e., better at verticality perception, suggesting that proprioceptive and vestibular expertise acquired by such exercise may weaken the influence of irrelevant visual signals. What remains unknown is whether the effect of body-related expertise in weighting perceptual information might also be mediated by personality traits, in particular those indexing self-focusing abilities. To explore this issue, we tested field-dependency in a class of body experts, namely yoga practitioners and in non-expert participants. Moreover we explored any link between performance on RFT and self-transcendence (ST), a complex personality construct, which refers to tendency to experience spiritual feelings and ideas. As expected, yoga practitioners (i) were more accurate in assessing the rod's verticality on the RFT, and (ii) expressed significantly higher ST. Interestingly, the performance in these two tests was negatively correlated. More specifically, when asked to provide verticality judgments, highly self-transcendent yoga practitioners were significantly less influenced by a misleading visual context. Our results suggest that being highly self-transcendent may enable yoga practitioners to optimize verticality judgment tasks by relying more on internal (vestibular and proprioceptive) signals coming from their own body, rather than on exteroceptive, visual cues.

Keywords: rod and frame test, self-transcendence, yoga, field dependency/independency, embodiment

INTRODUCTION

The perceived direction of upright, a process referred to as "subjective visual vertical" (SVV), is fundamental for our visual, interpretation of the world. SVV can be assessed by means of the rod and frame test (RFT), developed for the first time by Asch and Witkin (1948). The RFT requires the setting of a visual linear marker (i.e., a rod), embedded in a square luminescent frame, along the gravitational vertical. Importantly, achieving a good performance in the test requires one to ignore the frame. Individuals who are unable to set the rod upright, and instead set it tilted, are also classified as "field-dependent." Individuals who are able to ignore the misleading context of the frame, setting the rod upright, are classified as "field-independent." RFT performance depends on the integration of visual with internal bodily signals (e.g., vestibular and proprioceptive), and relies on a multisensory integration process that involves proprioception, vision, vestibular, and postural cues (Zoccolotti et al., 1992, 1993; Golomer et al., 2005; Luyat et al., 2005; Isableu et al., 2008; Lopez et al., 2008). Interestingly a similar process is involved in postural control (Massion, 1994). Changes in any of the above sensory inputs imply that individuals have to redefine the respective contribution of the different sources of information (Ernst and Bülthoff, 2004) for regulating posture and balance.

Self-transcendence (ST) is considered to be a dimension of character based on a synthesis of information about social and cognitive development and descriptions of personality development in humanistic and transpersonal psychology. According to a widely known psychobiological model of personality, inter-individual differences in spiritual feeling and thinking are detected by the Temperament and Character Inventory (TCI) (Cloninger et al., 1994; Gillespie et al., 2003) and cluster into a supposedly stable personality dimension called ST. ST measures the inclination of human beings toward spirituality, and generally refers to identification with everything conceived as a part of a unified whole reflecting the awareness of being an integral part of the universe (Paloutzian and Park, 2005). Highly self-transcendent people are characterized by great awareness of the self and of the environment (Reed, 2008). Cooperativeness (C) is a dimension of character that measures acceptance of other people, while ST captures the degree to which an individual feels that they are a part of nature and the universe at large (Gillespie et al., 2003). C is a dimension of character that defines the maturity of the self as part of a community or society and is linked to concepts like compassion, empathy, and tolerance (Cloninger et al., 1994).

Yoga, in general, involves a series of integrative mind-body exercises involving stretching, balance, bodily alignment, relaxation, meditation, and breathing. Thus, yoga may increase bodily awareness, in particular the perception of one's body in space (Yardi, 2001). We chose to study yoga practitioners because of their special expertise in body awareness. These individuals are characterized by an almost daily practice with enhanced focus on their body position in space (i.e., in vestibular-proprioceptive terms) and also by an overall embodied lifestyle. The focus on sensory experiences is at the core of many movement-based practices such as yoga. Ashtanga yoga (AY) is a branch of Hatha yoga focusing on physical exercise and non-visual experience of the body in space (Benavides and Caballero, 2009; Varambally and Gangadhar, 2012). Like other yoga experts, AY practitioners are involved in meditative practices (David et al., 2014). However, they have to master body representations that are likely involved in ST (Urgesi et al., 2010; Crescentini et al., 2014). One of the aims of body-mind practices is to reach a high level of ST, together with a deep awareness of one's own body and a non-judgmental attitude to life. Hatha yoga is proved to increase body awareness (Mehling et al., 2009), ST and well-being (Macdonald and Friedman, 2009), while mindfulness-oriented meditation (MOM) improves both C and ST (Campanella et al., 2014). It is held that a close relationship exists in the practice of yoga between the achievement of a stable equilibrium through physical exercises (i.e., to correctly execute poses) and an internal balance in a broader sense of living the present in harmony, accepting oneself, and finding peace. Thus, we sought to determine if there is any specific link between two crucial aspects of AY, namely verticality proprioception and balance for execution of yoga positions. Physical exercises and the development of specific skills may "shape" the mind by means of mechanisms of neural plasticity (Froeliger et al., 2012). Moreover, practicing sport typically enhances verticality perception, especially in experts in disciplines requiring a fine postural control (Golomer et al., 2005). Also, awareness of body orientation modulates the perception of the visual vertical (Barra et al., 2012). On the basis of previous literature we expect AY practitioners perform better in verticality estimation and are field independent. One of the aims of body-mind practices is to achieve high levels of ST, together with a deep awareness of one's own body and a non-judgmental attitude to life. C and ST are likely to be the most complex and evolutionary recent aspects of personality. Unlike temperamental variables, that are underpinned by a very wide subcortical and cortical neural network (Cloninger et al., 1994), the character dimensions, particularly ST, may be associated to cortical structures and be prone to the effects of specific environmental inputs (Urgesi et al., 2010; Crescentini et al., 2014). In view of this, we tested whether AY practice influenced the personality traits likely to be more susceptible to plastic changes. What remains unknown is whether personality traits like ST and C are linked to the perceptuo-motor behavior involved in SVV tasks. Here we used RFT to investigate whether expert yoga practitioners are more field-independent than non-experts. We expected that, like other motor experts (Golomer et al., 1999; Vuillerme et al., 2001b; Jola et al., 2011), yoga practitioners should not be very influenced by external visual cues in assessing SVV. We also explored whether differences in ST (probably higher in practitioners) are associated with differences in RFT performance.

METHODS

PARTICIPANTS

Data collection was performed at the department of Psychology at University of Rome "La Sapienza," School of Medicine and Psychology, in the period from January to April 2012. A group of 21 AY practitioners (aged 26–53 years, mean 37.14; mean education 18.38 years, range 13–25 years; 13 females) recruited at two AY schools in Rome, and 22 control participants (aged 26–52 years, mean 35.86; mean education 18.59 years, range 11–26 years; 13 females) with no expertise in yoga, or any meditation practice, participated in the study. Participants were matched for age [$t_{(41)} = 0.59, p = 0.561$], gender ($\chi^2 = 0.036, p = 0.85$), and education [$t_{(41)} = -0.178, p = 0.860$].

AY is a unique style of yoga that focuses on the non-visual experience of body in space. AY is taught in supervised self-practice, with teachers adjusting the student's body if the asanas (postures) are incorrectly maintained, without giving any other visual, or verbal instructions. There are no mirrors in the room; furthermore, the gaze remains focused on defined points on the body or room. Thus, to correctly achieve/maintain yoga asanas, participants must rely on a very good sense of their body in space, and on high skills in interpreting vestibular information coming from the body. Our yoga participants had been practicing for 3 months to 12 years (mean: 4.8 years) and were able to practice from 1st to 4th series of AY levels with 4 meaning the most advanced one (mean: 1.86 series). AY consists of four series/levels characterized by postures of increasing complexity. A practitioner can only advance to the next series if he/she can physically master all postures of that level. AY courses go well-over training weeks and achieving the highest levels may require years. All participants had normal or corrected-to-normal vision, and gave written informed consent prior to participating in the experimental tests. They received information concerning the experimental hypothesis only after completion of the tasks. Participants were paid 7.50 €/h for participation. All procedures were approved by the ethics committee of the IRCCS Santa Lucia Foundation (Rome), and were in accordance with the standards of the 1964 Declaration of Helsinki. All participants were unaware of the purpose of the experiment.

ROD-AND-FRAME TEST

APPARATUS AND STIMULI

A standard RFT device square frame was used, previously described in Zoccolotti et al. (1997). Each side of the square frame measured 96 cm, and a single 15 cm long rod was anchored at the center of the frame. Both the frame and the rod were outlined with 1.2 cm-wide fluorescent tape, and were the only visible elements in a completely darkened room. To prevent fading, the apparatus was exposed to light for 30 min before each session. Observers were seated in an erect position at a distance of 160 cm so that the square subtended a visual angle of 34° and the rod a visual angle of 5°. The frame was tilted 33° clockwise (CW), counter-clockwise (CCW), or not tilted (0°), the rod 11° or 22°, CW or CCW. Thus, there were 12 randomly presented conditions, each containing three trials (Takasaki et al., 2012) (see **Figure 1A** for example). Errors were calculated as deviation from the gravitational vertical position of the rod.

ASSESSMENT OF SELF-TRANSCENDENCE

Participants completed the scale of the Temperament Character Inventory (TCI) assessing ST, and cooperativeness (C), (Cloninger et al., 1994). These two personality traits were selected for their specific relationship with the so-called mind-body practices (i.e., meditation, mindfulness, relaxation, yoga, and tai-chi). Despite several differences, mind-body practices such as mindfulness yoga share meditation goals and do show close relationship with specific personality traits. It has been shown, for example, that MOM (Campanella et al., 2014) after 8-weeks training may increase ST (Campanella et al., 2014). Kemeny et al. (2012) found an increment in empathy and C after 8 weeks of contemplative training. In addition, yoga practice have the potential to increase mindfulness (Shelov et al., 2009), assessed by the Freiburg Mindfulness Inventory (FMI) (Walach et al., 2006). Thus, we sought to determine whether these personality traits are different in AY practitioners with respect to novices.

Individuals high in ST are described as patient, selfless, spiritual, and seem to tolerate ambiguity and uncertainty. The ST scale of the TCI consists of 33 statements, which describe attitudes, opinions, interests or personal feelings and which have to be evaluated as true or false according to the participant's personal opinions. ST includes three subscales: Self-Forgetfulness vs. Self-Consciousness (ST1), Transpersonal Identification vs. Personal Identification (ST2), and Spiritual Acceptance vs. Rational Materialism (ST3). Cooperativeness (C) is assessed with five subscales: Social acceptance vs. intolerance (C1), Empathy vs. social disinterest (C2), Helpfulness vs. unhelpfulness (C3), Compassion vs. revengefulness (C4) Principles vs. self-advantage (C5), and it consists of a total of 42 statements. This scale concerns the degree to which people are generally agreeable, in their relations with others, and how much they identify with and accept others. (see **Table 1** for example items).

PROCEDURE AND STATISTICAL ANALYSES

Participants were blindfolded and led into a dark blue painted room. The concept of verticality was defined using standard examples referring to familiar scenes (e.g., water running from the tap, door frame). Participants had to give verbal instructions to the experimenter in aligning the rod to the gravitational vertical position. No time limit for responses was given. Participants had to keep their eyes closed between trials.

To assess field dep/independency two indexes were used namely the Nyborg and Isaken equation (Frame Effect; Nyborg and Isaksen, 1974) and the Frame Influence. Please note that the Frame Effect is the sum of right-frame tilted trials (CW) divided by the number of right-frame tilted trials, minus the overall mean error in frame tilted condition, calculated by summing up both left-frame tilted (CCW) and right-frame tilted (CW) trials divided by total numbers of trials:

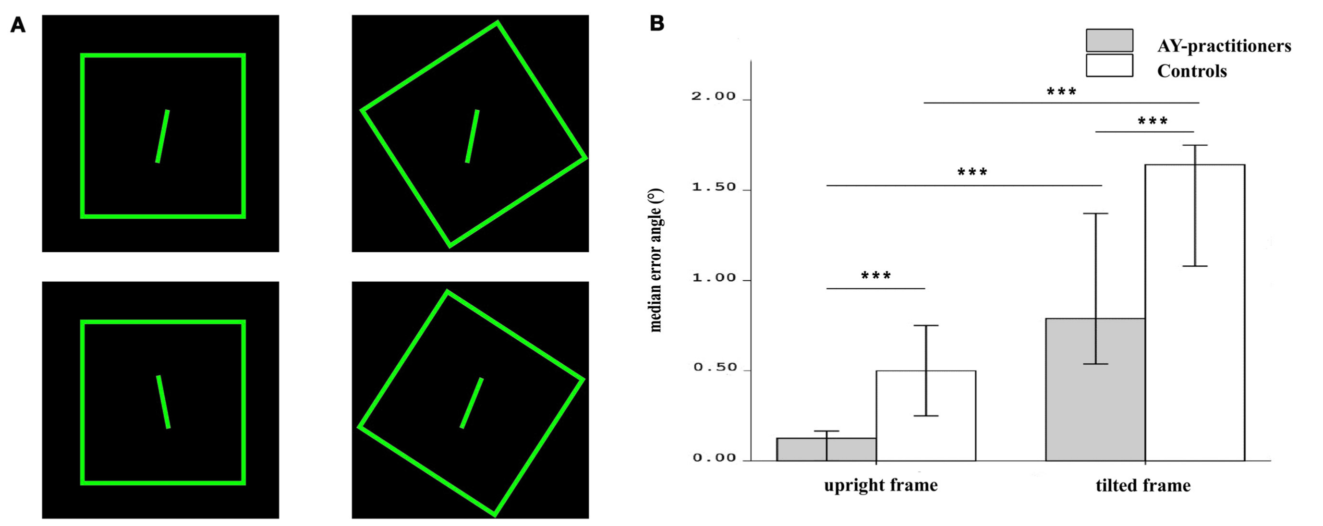

FIGURE 1 | Example of RFT experimental set-up and results. **(A)** Participants were seated in front of a large fluorescent frame inside a completely darkened room (left panel). The frame was either tilted or vertical. Inside this frame, approximately at the same level as the eyes, there was a tilted rod, which participants had to verbally set to the vertical (i.e., end angle of the rod 0°). **(B)** Displayed is the median error angle (°), that is the median value of deviation from the gravitational vertical position in the tilted and non-tilted frame condition in both groups. Ashtanga yoga showed significantly smaller deviations of the SVV from the earth vertical when the frame was tilted as compared to novice participants. Furthermore, practitioners and control group, in a with-in comparison, performed better in the upright frame conditions than in the tilted condition. Error bars reflect confidence level at 95%. All tests were two-tailed. Asterisks in the plots indicate significance levels: $^{***}p < 0.001$.

Table 1 | Exemplary Items for each of the sub-scale of the self-transcendence and cooperativeness dimensions as assessed by the temperament and character inventory.

		Sub scale	Exemplary item
Self-transcendence	ST1	Spiritual acceptance vs. rational materialism	I believe that miracles happen
	ST2	Self-forgetful vs. self-conscious experience	Often I have unexpected flashes of insight or understanding while relaxing
	ST3	Transpersonal identification vs. self-differentiation	I often feel a strong sense of unity with all the things around me
Cooperativeness	C1	Social acceptance vs. social intolerance	I have no patience with people who don't accept my views
	C2	Empathy vs. social disinterest	I wish other people didn't talk as much as they do
	C3	Helpfulness vs. unhelpfulness	I try to cooperate with others as much as possible
	C4	Compassion vs. revengefulness	Most of the time I quickly forgive anyone who does me wrong
	C5	Pure-hearted conscience vs. self-serving advantage	Principles like fairness and honesty have little role in some aspects of my life

$$\frac{\text{CWtrial1} + \text{CWtrial2} + \cdots + \text{CWtrialn}}{\text{nCWtrials}} - \frac{\text{CWtrial1} + \text{CWtrial2} + \cdots + \text{CWtrialn} + \text{CCWtrial1} + \text{CCWtrial2} + \cdots + \text{CCWtrialn}}{\text{nCCW trials} + \text{nCW trials}}$$

The Frame Effect index represents the attraction of a perturbing visual field on the subjective vertical. For the purpose of this experiment it was not necessary to know the frame effect direction (CW or CCW). Thus, the frame effect index was used considering absolute values.

A different index of the strategy used in SVV estimation was assessed by subtracting the mean end angle error collapsed against rod and frame upright condition to the mean end angle error collapsed against rod and frame tilted condition (*FR_Tilted_All Rod)-(FR_Non-Tilted_All Rod*). This index (which we called Frame Influence) is independent from the tilt angles and from the participants' ability in estimating verticality, and it may highlight the two different perceptual styles (i.e., field dependency/independency), along a continuum. Higher values indicate that verticality is estimated using mainly a visual strategy. By contrast, low values indicate that verticality is estimated mainly using a proprioceptive or vestibular strategy. The Frame Influence differs from the Nyborg's Frame Effect because it takes into account the errors made by participants in assessing verticality in the upright frame position. The Frame Influence index describes visual context dependency. Frame tilted conditions (CCW and CW) and rod conditions (CCW vs. CW and 11 vs. 22°) were collapsed because the aim of this study was to evaluate the size of the errors in assessing SVV and not the direction of the errors (CCW vs. CW). To test the null-hypothesis that data are normally distributed we used the Shapiro–Wilk test. In the event that data were non-normally distributed, Mann–Whitney and Wilcoxon signed-rank tests were used for between-group and within-group comparisons, respectively. When data were distributed normally, Student t-tests were used. Differences in personality traits between AY practitioners and control group have been computed by appropriate between group comparison analysis. To test if any relationship exists between personality traits and bodily processing involved in RFT performance, a correlational analysis was performed. Analyses were conducted using the SPSS software package (version 17.0, SPSS Inc., Chicago, IL, USA). To ascertain if participants are more biased in verticality estimation in CW or CCW frame condition, or when the rod was settled at 11 and 22°, in CW or CCW position, a Friedman ANOVA was performed. If no differences are found, an overall mean across tilted and non-tilted frame conditions can be used.

RESULTS

ROD-AND-FRAME

RTF accuracy analysis was performed by collapsing all rod conditions (11 and 22°, CW and CCW) and then comparing the overall mean error in the tilted-frame vs. the overall mean error in the non-tilted frame conditions. Friedman's test was used before collapsing variables. No differences were found in frame tilted [Friedman test; χ^2_{AY} $(7, n = 21) = 7.711$, $p > 0.05$; χ^2_{Con} $(7, n = 22) = 13.293$, $p > 0.05$] and upright [Friedman test; $\chi^2_{AY}(3, n = 21) = 1.691$, $p > 0.05$; χ^2_{Con} $(3, n = 22) = 3.091$, $p > 0.05$] position in both groups. The following variables were then used for the main analysis: FR_Tilted_All Rod represents the mean error of all trials in tilted condition, irrespectively to the rod starting position, and FR_Non-Tilted_ All Rod summarizes all trials in frame upright condition irrespectively to the rod starting position.

To determine differences in accuracy in assessing SVV the overall mean error in the tilted-frame vs. the non-tilted frame conditions were compared in AY practitioners vs. control group. AY practitioners were less biased by the context of a tilted frame in adjusting their SVV (Mdn = 0.79°, IQR = 0.50) compared to controls (Mdn = 1.64°, IQR = 0.72) (Mann–Whitney test; $U = 88$, $p < 0.001$). AY practitioners were also more accurate in judging verticality in the frame non-tilted condition (Mdn = 0.12°, IQR = 0.20) compared to controls (Mdn = 0.50°, IQR = 0.59); [Mann–Whitney test; $U = 86$, $p < 0.001$]. Both groups were more accurate in SVV estimation in the non-tilted condition, (Wilcoxon signed-rank test; $T_{AY} = 0.00$, $p < 0.001$; $T_{Con} = 1.00$, $p < 0.001$), hinting at a similar effect of the presence of the frame (see **Figure 1B**).

The mean value Ashtanga practitioners Frame Effect was slightly lower (mean = 0.25°, $SD \pm 0.24$) than those obtained by controls (mean = 0.37°, $SD \pm 0.30$). No significant between group comparison was found [*Frame Effect* $t_{(41)} = -1.348$, $p > 0.05$]. This indicates that the presence of the frame affected the RFT performance similarly in AY and controls. Frame Effect absolute value, tested against a reference constant (value = 0), turned out to be significant in both groups [$t_{AY(20)} = 4.36$, $p < 0.001$; $t_{Con(21)} = 5.76$, $p < 0.001$].

In order to analyse the strategy used by participants in assessing SVV, the Frame Influence index was used. AY practitioners (mean = 0.74°, $SD \pm 0.38$) and Controls (mean = 1.08°, $SD \pm 0.84$) seem to use the same strategy in assessing SVV, $t_{(41)} = -1.68$, $p > 0.05$.

OBSERVED RANGE IN SELF-TRANSCENDENCE

AY practitioners scored significantly higher in ST (mean score = 19.48, range 4–29) compared to control participants (mean score = 11.27, range 2–22); $t_{(41)} = 3.957$, $p < 0.001$ (**Figure 2A**). AY practitioners scored significantly higher in all ST subscales and since the effect was comparable for the three ST sub-scales, the total ST score was used for the correlation analysis. In the C subscale no statistical difference between groups was found (all $p > 0.05$), therefore relationships between variables were run only for variables statistically different (see **Table 2** for all results).

CORRELATION ANALYSIS

Correlation analysis has been run only on Frame Influence and ST score because this index is much more adept to inform about the strategy used by participants to assess verticality. The Frame Effect measures how much the presence of a tilted frame influences the verticality assessment, on the basis of visual distracting cues and not of participants' performance in the upright condition. In our opinion the ability to assess verticality in upright frame condition can be considered as a baseline. This can be important for understanding whether the internal model of verticality is necessarily upright and whether the frame has to be necessarily present in the computing od field dep/independency. Thus, the Frame Influence index describes the ability to remain stable in verticality estimation irrespectively of whether the frame is tilted or not. The Pearson correlation in all participants collapsed together was as follows: $r = 0.009$, $p = 0.957$, $n = 43$. Since the study focused on differences between two groups, the correlation was also performed in the two groups separately. A significant negative Pearson correlation between Frame Influence and ST scores was found in AY practitioners ($r_{AY} = -0.515$, $p = 0.020$, $n = 20$; **Figure 2B**). Note that one outlier participant was removed from the sample on the basis of the residual analysis. No such correlation was found in the Control group ($r_{Con} = 0.408$, $p = 0.059$, $n = 22$). Thus, in AY practitioners, the higher the ST the smaller the influence of the tilted frame.

DISCUSSION

In this study we investigated the link between the processing of bodily signals assessed by the RFT, AY (a specific type of yoga aiming at increasing body awareness) practicing and dispositional ST. Four main results are reported: (1) AY practitioners performed better than controls in the verticality judgment task in all RFT conditions; (2) both AY and Controls can be considered as field dependent, when using the Frame Effect (Nyborg and Isaksen, 1974); (3) AY practitioners showed higher ST compared to non-yoga practitioners; (4) a negative correlation between "Frame Influence" index and ST scores was found in AY but not in the novice group.

PROCESSING OF SENSORY INPUTS CONCERNING BODY AND SPATIAL ORIENTING REQUIRED FOR PERFORMING RFT AND PRACTICE OF ASHTANGA YOGA

Visual dependence from a given context has been measured in professional dancers who performed RFT with a style more independent from vision with respect to non-dancers (Golomer et al., 1999, 2005). In a similar vein, gymnasts exhibited better postural control than novices (Vuillerme et al., 2001a; Croix

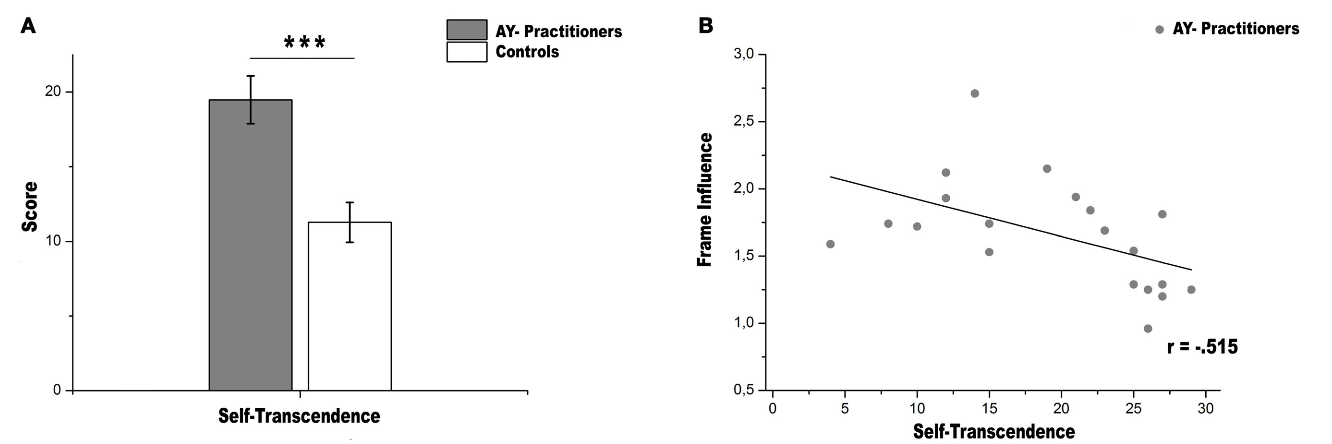

FIGURE 2 | Personality trait and Rod-and-Frame performance. **(A)** self-transcendence scores. Ashtanga yoga are significantly more self-transcendent than controls group (error bars reflect s.e.m). Asterisks in the plot indicate significance level, ***$p < 0.001$. **(B)** "Frame Influence" negatively correlates with scores on ST in Ashtanga yoga, proving that the more they use a proprioceptive style strategy in assessing the SVV (small value in "Frame Influence" index), the more they are self-transcendent.

Table 2 | Table shows scale range, mean, observed range and differences between groups for each subscale of ST and C scales.

	Sub scale	Range	AY		Con		*t*-value (41)	*p*-value
			Mean	Observed range	Mean	Observed range		
ST tot	Self-transcendence	0–33	19.48	4–29	11.28	2–22	3.957	0.0003
ST 1	Spiritual acceptance vs. rational materialism	0–13	7.33	1–12	4.56	1–11	2.666	0.011
ST 2	Self-forgetful vs. self-conscious experience	0–11	6.39	1–10	4.37	0–9	2.359	0.023
ST3	Transpersonal identification vs. self-differentiation	0–9	5.76	2–9	2.32	0–6	6.140	0.000003
C tot	Cooperativeness	0–42	35.19	29–40	33.50	18–39	1.362	0.181
C 1	Social acceptance vs. social intolerance	0–8	6.57	1–8	6.81	4–8	−0.564	0.576
C 2	Empathy vs. social disinterest	0–7	6.24	4–7	5.68	2–7	1.675	0.102
C 3	Helpfulness vs. unhelpfulness	0–8	6.86	5–8	6.59	4–8	0.863	0.393
C 4	Compassion vs. revengefulness	0–10	8.29	5–10	7.59	1–10	1.291	0.204
C 5	Pure-hearted conscience vs. self-serving advantage	0–9	7.24	2–9	6.82	4–9	0.923	0.361

et al., 2010), even when the contribution of vision is removed (Vuillerme et al., 2001b). It is also worth noting that in kayak roll athletes who, in structured training sessions, learn specific sub skills (i.e., underwater orientation, paddle movements), greater field-independence (measured with a portable rod and frame apparatus) may parallel fast learning of the training skills. Kayak roll requires cognitive restructuring and strong reliance on kinaesthetic and proprioceptive feedback (Hodgson et al., 2010). AY practitioners typically report the discipline induces an embodied life style, in keeping with the objective need to rely on one's body perception in space for achieving good progress in this discipline. Importantly, any differences between AY and novices in RFT performance cannot be attributed to visual practice, because no visual cues are used in the discipline, no visual feedback is given from mirrors, and the practice is based exclusively on the close connection with the body and the awareness of its position in space.

Thus, we did not find that AY practitioners are more field independent than non-experts. One possible way of interpreting this seeming discrepancy is to consider that our very conservative method to assess field dependency/independency (frame effect = 0) was never used in any previous studies.

While superiority of AY practitioners in the RFT task may not be surprising, no specific conclusion on whether they are more field independent can be drawn.

It is also worth noting that the field-independences as assessed by Nyborg's Frame Effect turned out to significantly differ from 0 in both AY practitioners and novice participants, indicating both groups are equally biased, in evaluating SVV, by the presence of a tilted frame and can be considered field-dependent. In fact, field-independent individuals should not be biased by the frame presence, and their errors (distance in degrees from SVV and earth-gravity) should be near zero, in both frame conditions (tilted or upright). By contrast, field-dependent individuals should make large errors in tilted condition but small errors, if any, in upright frame condition.

The lack of difference in Frame Effect between the two groups is consistent with the assumption that the two groups mainly differ for yoga practice, a physical training designed to increase balance. It is worth noting that no visual cues are used in AY and the practice is based exclusively on the close connection with the body and the awareness of its position in space. Moreover, no visual feedback is given to AY practitioners.

The Frame Influence index describes a perceptive style in assessing the rod in upright position, without taking into account the performance on RTF. Interestingly, the Frame Influence index may allow researchers to virtually divide participants into two sub-groups on a continuum with people who make errors of the same size in tilted and non-tilted frame conditions, and people making large errors in frame-tilted and small ones in non-tilted conditions. People with a high Frame Influence index base their verticality estimation more on the visual system, gaining useful cues in non-tilted condition, but being deceived by the frame in the tilted condition. By contrast, people with a low Frame Influence index adopt a strategy based more on proprioceptive signals without taking the frame angle into account. Thus, individuals who make large errors both in frame tilted and upright condition base their verticality perception on proprioception. By contrast, individuals who provide exact judgment of verticality only in the upright condition, but make large errors in the frame-tilted ones, base their perception of verticality on external visual cues. At any rate, the Frame Influence index may be interpreted as a marker of perception style that gives information about people who determine their verticality perception using more the proprioceptive than the visual system. It is worth emphasizing that the practice of AY usually takes place in places without any mirror and in the absence of visual feedback. Thus, AY practice is based more on proprioception than on visual feedback. No between-group difference in the Frame Influence index was found, indicating that, in spite of the superiority of AY practitioners in performing the RFT task, the two groups did not differ in the strategy used for estimating verticality. This lack of difference may be attributed to the fact that our yoga Asthanga practitioners were mostly beginner-intermediate and no specific analysis on advanced level practitioners could be performed. A possible explanation of this lack of difference may reside in the fact that yoga does increase precision in verticality estimation, but does not induce any change in field-dependency.

A LINK BETWEEN ASHTANGA YOGA AND SELF-TRANSCENDENCE

Our finding shows that yoga practitioners are more self-transcendent than novices. To the best of our knowledge, the study by Büssing et al. (2012) is the only exploring ST related to yoga practice. They adopted a within-subject design, in which Yoga practitioners were enrolled in an intense training for becoming yoga teachers and found showed an increase of ST in yoga practitioners after 6 months of intensive training. These results may suggest that Yoga practice increases ST and specific aspects of practitioners' spirituality, mindfulness and mood. However, ST was higher in yoga practitioners than in the reference control population already before the training. Thus, neither Büssing et al. (2012) study nor our present results can tell apart whether higher ST is the direct consequence of yoga practice or the expression of a tendency to adopt a specific lifestyle.

RELATIONSHIP BETWEEN BODILY PROCESSING AND ST

AY practitioners and the control group did not statistically differ in Frame Influence index. Importantly, however, only in this group there were a relationship between higher ST scores found in individuals with smaller Frame Influence. Thus, highly ST individuals are more in touch with their body, and may be better at analysing information coming from their body. The same correlation was not found in non-yoga practitioners.

Yoga practice is deeply connected with meditative experiences and mindfulness training. There have been reports, for example, of better performance in RTF performance in a group that underwent a 3-months transcendental meditation training compared with a group who did not receive this kind of treatment (Pelletier, 1974). All participants were tested also in an auto kinetic effect and an embedded figure test (EFT; Witkin, 1950) a task designed to assess the concept of field dependence/independence (Witkin and Goodenough, 1981). The meditation group improved their performance in all tasks after 3 months of training. These better performances have been ascribed to an increased field-independence. While this is true for the result obtained in the EFT, participants shifted toward a shorter latency time for the simple figure identification, only a reduction in the error size has been noted in the RFT, and no frame effect was measured. Attention is a critical factor in determining performance in these perceptual tasks. Interestingly one of the most important aims of meditative techniques is to achieve an inward, focused attention. In this context, Pelletier (1974) suggested that these observed differences can be attributed to an alteration in the individual's displacement of attention toward a context-independent cognitive style, due to meditative practice.

It would be interesting to investigate if there is a difference in the "Frame Influence" index between very advanced practitioners (3rd and 4th level), beginners (1st and 2nd level), and novices. Unfortunately in this study it was only possible to collect two practitioners from 3rd level and only one from 4th level.

Our results are partially in conflict with the findings of Hergovich (2003) who showed a relationship between field dependence, measured by EFT, and belief in paranormal phenomena. In Hergovich's study, participants completed several questionnaires assessing belief in paranormal phenomena, while we used the TCI (Cloninger et al., 1994) for assessing ST. A closer inspection of the items revealed that especially the subscale ST-1 shares some elements with the questionnaires administered by Hergovich. For example, in both tests there are items related to phenomena not easily explained by science, alternative medical practices, and near-death experiences. In spite of this possible similarity, it is worth noting that while the questionnaires used by Hergovich (2003) assess beliefs, ST scales assess a specific personality trait. In AY, we found higher field independence and reliance on internal information depending on higher ST scores. An opposite, non-significant tendency, was found in the control group, where high ST scores paralleled field-dependence and reliance on visual cues in SVV tasks. Only the result in healthy controls is in keeping with Hergovich (2003). While we do not have a ready explanation for this partial discrepancy, we note that using different tools for testing field dependency may bring about different results (Arbuthnot, 1972). Thus, although speculatively, we suggest that the difference between the two studies may be explained by the different sensitivity of the tools used. In any case, the different patterns of results in yoga practitioners may be due to a training effect from the embodied experiential practice of AY, that may change reliance on internal signals (i.e., interoceptive, proprioceptive, vestibular). No such learning effect may have occurred in novices. It is worth noting that temporo parietal junction (TPJ), a neural region that is supposed to be an important function in the body's space proprioception (Trousselard et al., 2004; Barra et al., 2012), is also important in body awareness (Bunning and Blanke, 2005; Aglioti and Candidi, 2011), and in integration of signals coming from our own body. It is also interesting that individuals who have experienced out-of-body experiences showed damage to multisensory cortices (Blanke et al., 2004; Lenggenhager et al., 2006; Ionta et al., 2011) centered around TPJ that may also be closely related to the processing of vestibular inputs (Lopez and Blanke, 2011; Lopez et al., 2012). Finally, alterations of TPJ induced by brain lesions (Urgesi et al., 2010), or by inhibitory TMS (Crescentini et al., 2014), induce an increase of ST and of spirituality. The hypothesis that TPJ is involved in both ST (i.e., spirituality) and the perception of the vertical midline has not been clearly tested. However, the question of whether TPJ may be important for performing RTF tasks is currently being investigated at our laboratory.

CONCLUSION

We report a relationship between the strategy used to assess verticality and ST only for yoga practitioners. This finding may index some changes in the mechanisms underlying the performance in verticality judgment depending on the personality traits likely influenced by yoga practice itself. More specifically, high levels of ST may guide people to deeper levels of body awareness mediated more by internal (i.e., vestibular or proprioceptive) than external signals. This finding may suggest that individuals who score high in ST have high levels of body awareness and rely more on internal (i.e., vestibular or proprioceptive) than external signals, as proposed by predictive models of interoception (Seth et al., 2011; Seth, 2013). The higher accuracy found in the overall mean, in both frame conditions, may rely on multisensory integrative systems through which optimization of the most reliable information takes place. Moreover, the lack of difference in the strategy used by participants in assessing verticality and in the frame effect index suggests that physical practice can account for accuracy in assessing verticality but not for changes of cognitive style. Yoga practice is a highly embodied discipline that, maybe through an enhancement of ST, allows one to achieve deeper body awareness; this process may be the key for accessing an embodied sense of balance/verticality, and consequently to achieve a more explicit improvement in sensory evaluation.

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Tai Chi training may reduce dual task gait variability, a potential mediator of fall risk, in healthy older adults: cross-sectional and randomized trial studies

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Background: Tai Chi (TC) exercise improves balance and reduces falls in older, health-impaired adults. TC's impact on dual task (DT) gait parameters predictive of falls, especially in healthy active older adults, however, is unknown.

Purpose: To compare differences in usual and DT gait between long-term TC-expert practitioners and age-/gender-matched TC-naïve adults, and to determine the effects of short-term TC training on gait in healthy, non-sedentary older adults.

Methods: A cross-sectional study compared gait in healthy TC-naïve and TC-expert (24.5 ± 12 years experience) older adults. TC-naïve adults then completed a 6-month, two-arm, wait-list randomized clinical trial of TC training. Gait speed and stride time variability (Coefficient of Variation %) were assessed during 90 s trials of undisturbed and cognitive DT (serial subtractions) conditions.

Results: During DT, gait speed decreased ($p < 0.003$) and stride time variability increased ($p < 0.004$) in all groups. Cross-sectional comparisons indicated that stride time variability was lower in the TC-expert vs. TC-naïve group, significantly so during DT (2.11 vs. 2.55%; $p = 0.027$); by contrast, gait speed during both undisturbed and DT conditions did not differ between groups. Longitudinal analyses of TC-naïve adults randomized to 6 months of TC training or usual care identified improvement in DT gait speed in both groups. A small improvement in DT stride time variability (effect size = 0.2) was estimated with TC training, but no significant differences between groups were observed. Potentially important improvements after TC training could not be excluded in this small study.

Conclusion: In healthy active older adults, positive effects of short- and long-term TC were observed only under cognitively challenging DT conditions and only for stride time variability. DT stride time variability offers a potentially sensitive metric for monitoring TC's impact on fall risk with healthy older adults.

Keywords: Tai Chi, gait analysis, dual task performance, falls and fall risk prevention, cognition

Introduction

The ability to walk while simultaneously performing a secondary cognitive task – commonly referred to as a dual task (DT) – is essential to many activities of daily living such as successful ambulation while navigating complex environs and conversing with others. Increasing evidence from clinical practice, epidemiological studies, and clinical trials show that postural control, gait health, and cognition are interrelated in older adults (Montero-Odasso et al., 2012). Observational studies have reported that the magnitude of the decrement in gait performance during a DT (i.e., the DT "cost") is higher in elderly fallers as compared to non-fallers (Springer et al., 2006), and recent long-term prospective epidemiological studies demonstrated that gait performance, and especially stride-to-stride variability, during a DT may be a particularly sensitive predictor of falls in older adults (Herman et al., 2010; Mirelman et al., 2012). The importance of cognition in gait performance and postural control is further supported by a growing body of studies employing a variety of neuroimaging (e.g., fMRI, fNRIS) and neurostimulation techniques (e.g., tDCS, TMS), which suggest that gait and executive function may share a network of brain regions in the frontal and parietal cortex (Gatts and Woollacott, 2006, 2007; Halsband and Lange, 2006; Mirelman et al., 2014; Zhou et al., 2014), often referred to as the fronto-parietal executive control network (Tessitore et al., 2012; Markett et al., 2014).

Growing appreciation of the interdependence of cognitive and postural control processes has led to search for multimodal interventions combining motor and cognitive training for improving gait and preventing falls (Mirelman et al., 2013; Kayama et al., 2014; Shema et al., 2014). Tai Chi (TC) is a multi-component mind–body exercise that is growing in popularity, especially among older adults (Wayne and Fuerst, 2013). TC integrates training in balance, flexibility, and neuromuscular coordination with a number of cognitive components including – heightened body awareness, focused mental attention, imagery, multi-tasking, and goal-oriented training – which together may result in benefits to gait health and postural control, beyond conventional unimodal exercise (Wayne et al., 2013). Evidence supports the idea that TC can improve balance and reduce fall risk in healthy and neurologically impaired older adults (McGibbon et al., 2004; Li et al., 2012; Manor et al., 2013), and may impact multiple aspects of gait health (McGibbon et al., 2005; Wu and Hitt, 2005; Wu and Millon, 2008; Vallabhajosula et al., 2014). Additionally, clinical and neurophysiological data indicate that TC may attenuate age-related cognitive decline, including executive function, which is critical to dynamic postural control (Wei et al., 2013; Hawkes et al., 2014; Wayne et al., 2014b). However, the potential for TC to reduce cognitive–motor interference, and specifically to improve gait performance during a DT activity, has not received much attention (Amano et al., 2013; Manor et al., 2014).

The current study evaluates the impact of both long- and short-term TC training on gait speed and stride time variability during both undisturbed (single task) walking and walking with a cognitive DT challenge. Long-term training effects were assessed through observational comparisons of TC naïve healthy older adults and an age-matched sample of expert TC practitioners. Short-term effects of TC training were assessed by random assignment of the TC naïve healthy adults to either 6 months of TC plus usual care or usual care alone. Based on research to date, we predicted that (1) TC experts would exhibit greater walking speed and reduced variability, compared to controls, and that group differences would be greater under DT challenges; (2) TC-naïve older adults randomly assigned to 6 months of TC would subsequently exhibit greater walking speed and reduced stride time variability; and (3) improvements in walking speed and reduced stride time variability observed over 6 months would be greater in those randomized to TC compared to a usual care control, with between-group differences being greater under DT challenges.

Methods

Study Design

We employed a hybrid study design that included a two-arm randomized clinical trial (RCT) along with an additional observational comparison group. The Institutional Review Board at Beth Israel Deaconess Medical Center approved this study. The RCT component of this study was registered at clinicaltrials.gov (NCT01340365). Gait outcomes reported herein are a subset of a larger battery of assessed outcomes including balance, cardiovascular, and cognitive outcomes. These latter outcomes are reported independently (Wayne et al., 2013, 2014a).

Randomized Trial Design

Sixty healthy older adults, aged 50–79, were randomized 1:1 to receive 6 months of TC training in addition to usual health care, or to usual health care alone (control group). Study participants randomized to usual care were offered a 3-month course of TC as a courtesy following the trial. Randomization was stratified by age (50–59, 60–69, 70–79 years) and utilized a permuted-blocks randomization scheme with randomly varying block sizes. Randomization was performed by the study statistician. All outcomes were assessed at baseline and 6 months, i.e., after completing 6 months of training. The primary staff overseeing assessment and analyses of the gait-related outcomes was blinded to treatment assignment. Recruitment spanned from March 2011 to March 2013. All follow-up procedures were completed by September 2013. Analysis was performed in 2014. Further details related to the design of the RCT component of this study are reported elsewhere (Wayne et al., 2013).

Recruitment for the Randomized Trial Targeting Community-Dwelling Healthy Adults

Inclusion criteria were (1) age 50–79 years; (2) living within the Greater Boston area; and (3) willing to adhere to a 6-month TC training protocol. Exclusion criteria were (1) chronic medical condition including cardiovascular disease, stroke, active cancer; neurological conditions; or significant neuromuscular or musculoskeletal conditions requiring chronic use of pain medication; (2) acute medical condition requiring hospitalization within the past 6 months; (3) self-reported inability to walk continuously for 15 min unassisted; (4) regular TC practice within past 5 years; and (5) regular participation in physical exercise on average 4 or more times per week. Interested individuals underwent both an initial phone screen and an in-person screen at the BIDMC Clinical Research Center. Eligible individuals provided written informed consent and underwent baseline testing prior to randomization.

Participants within both groups were encouraged to follow usual health care as prescribed by their primary care physicians. Participants in the TC group received 6 months of TC training in addition to usual care. All TC interventions were administered pragmatically at one of five pre-screened TC schools within the Greater Boston area that met specific guidelines described elsewhere (Wayne et al., 2013). Study participants were asked to attend, on average, two classes per week over the 6-month intervention. They were also asked to practice a minimum of 30 min, two additional days per week. Attendance at TC classes was recorded by instructors and home practice was tracked by participants using a weekly practice log. Participants that reported attending a minimum of 70% of all classes and completing 70% or more of prescribed home practice between each study visit were considered compliant or "per-protocol." Adverse events were systematically collected from participants and instructors and are reported elsewhere (Wayne et al., 2014a).

Non-Randomized Comparison Group: Tai Chi Experts

Twenty-seven healthy older adults (age 50–79 years) currently engaged in an active TC training regimen, each with over 5 years of TC practice, were recruited for a single observational visit. No limitation was set on TC style. Eligibility and screening procedures for TC experts were identical to those for healthy adults enrolled in the RCT.

Measurements

Participants reported to the Beth Israel Deaconess Medical Center's Clinical Research Center (Boston, MA, USA) where they underwent in-person screening procedures. Participants with a mini mental state examination (MMSE) score $\geq$24 and no abnormal findings on an ECG were eligible to participate in the study. All outcome measurements were assessed at the Syncope and Falls in the Elderly (SAFE) laboratory at Beth Israel Deaconess Medical Center. Outcomes related to gait reported here were part of a larger battery of tests that lasted an average of 3.5 h. Changes in DT gait speed and gait variability from baseline to 6 months were *a priori*-defined outcome measures of primary interest.

Assessment of Gait

Gait was assessed along a 75-m long unobstructed hallway. Subjects were instructed to walk at their normal preferred walking pace and make wide turns at the ends of the hallway. Two 90 s walking trials were completed: undisturbed with no superimposed cognitive task (i.e., single task walking) and walking while completing a cognitive DT. The cognitive DT consisted of a serial subtraction exercise counting backwards by threes beginning at 500. Ultrathin, force-sensitive resistor footswitches were placed on each subject's heel and toe to capture the temporal parameters of gait. Data were collected wirelessly at 1500 Hz with DTS Data Acquisition Software (Noraxon, Scottsdale, AZ, USA). The data for each trial was exported and analyzed in Matlab (Mathworks, Natick, MA, USA) to determine initial and final foot contact times for each stride. Stride times were calculated for each gait cycle as the time between initial heel strike of one foot and the subsequent heel strike of that same foot. Average gait speed was measured using the total distance walked during the trial. Stride time variability was calculated from the stride time time-series as the coefficient of variation (CV, 100 multiplied by the SD of the stride times divided by the mean of each subject's stride times). To calculate these measures, the first five strides were removed to minimize potential gait initiation effects. A median filter was applied to the stride time time-series to remove large outliers, typically a result of turns at the ends of the hallway. This ensured that the steady state variability was analyzed for each time series. Average stride time and stride time variability was determined from the resultant time series.

Dual task costs were calculated using both absolute and proportional measures. Absolute DT costs (Abs. DT) were calculated for each participant as the difference in walking speed or stride time variability between undisturbed single task walking (ST) and DT walking. Proportional DT costs (% DT) were calculated for each participant's walking speed or stride variability as: $100 \times ((DT - ST)/ST)$. Both the number and the accuracy of serial subtractions during DTs were recorded.

Baseline Cognitive Function and Physical Activity

Global cognitive function at baseline was assessed with the MMSE. Executive cognitive function was assessed using the trail making test (TMT B and TMT B-A) (Bowie and Harvey, 2006; Sanchez-Cubillo et al., 2009). TMT B assesses the time required to connect a series of circles in an alternating sequence of numbers and letters (e.g., 1-A-2-B-3-C). TMT B is considered to evaluate executive control, and is correlated with other executive function measures (Arbuthnott and Frank, 2000). TMT B is a sensitive indicator of overall neurological impairment and has good reliability (Bowie and Harvey, 2006). TMT A assesses the time required to connect a series of numbers. The difference between TMTB and A more accurately assesses executive function since it corrects for processing speed. Physical activity level was assessed using the physical activity status scale (PASS). Subjects were asked to estimate their general physical activity during the previous week using an 11-point scale (i.e., 0–10). The scale quantifies physical activity duration by a combination of the minutes of exercise per week and the intensity of this exercise (i.e., heavy, modest, or none) (Heil et al., 1995; Jackson et al., 1995).

Statistical Analysis

Cross-sectional measures of gait outcomes in TC experts and TC naïves were compared in a linear model controlling for age, gender, BMI, and physical activity and assuming equal variance across groups. For measures where the assumption of equal variance may have been violated, the larger of the two groups, the TC naïves, had greater estimated variance, leading to potential overestimates of pooled variance and conservative estimates of effect sizes and *p*-values. Inference was unchanged when applying an equivalent generalized least squares model allowing for variance heterogeneity between groups. Trajectories of gait performance over the 6-month intervention were compared between naïve participants randomized to TC or usual care using a random-slopes model with shared baseline. All longitudinal analyses were conducted according to the intention-to-treat paradigm. The model included fixed effect of time, time × treatment, age, gender, BMI, physical activity, and interactions between time and age, gender, BMI, and physical activity. The model included random participant-specific intercepts and slopes with unstructured covariance. The shared baseline assumption, enforced by omitting a treatment main-effect term, properly reflects the true state of the population sampled prior to randomization and has the advantage of adjusting for any chance differences at baseline (Zeger and Liang, 1986). Treatment-group differences and adjusted means for a male participant with mean age, BMI, and physical activity were estimated as well as their 95% confidence intervals. Both cross-sectional and longitudinal effect size estimates were calculated using pooled baseline SDs after adjusting for age, gender, BMI, and physical activity (Feingold, 2013). All inferential tests were two-tailed with alpha set at 0.05. We chose to report comparison-wise *p*-values without adjustment for multiple comparisons to avoid inflating type II errors, recognizing that the nominal *p*-values underestimate the overall experiment-wise type I error rate. Our results are intended as hypothesis generating, not definitive tests of efficacy for TC on any specific measure of gait. No comparisons were significant after a step-down Bonferroni adjustment for multiple comparisons. All analyses were performed in SAS (version 9.3, SAS Institute, Cary, NC, USA).

Sample Size Considerations

For cross-sectional comparisons, we estimated that a sample size of 27 TC Expert and 60 TC naïve subjects would provide power to detect an effect size of 0.63. For the randomized trial, we estimated that the sample of 60 participants randomized 1:1, the study would have 80% power to detect a main effect of treatment if the true effect size was at least 0.74 based on a two-tailed test at $p < 0.05$.

Results

Baseline Characteristics and Study Flow

Demographic characteristics of the TC experts ($n = 27$) were well-matched with the older TC naïve group with respect to average age and cognitive status as measured by MMSE and trial making B test. Compared with naïve older controls, experts included a slightly greater proportion of men and Asians, had lower BMI's, and higher levels of physical activity (see **Table 1**). TC experts reported an average of 24.6 ± 12 years of TC training experience (median: 20 years, range 10–50 years). Approximately equal numbers reported Yang ($n = 12$) and Wu ($n = 15$) style TC as their primary training systems; however, all reported having training experience in others styles of TC-related internal and external martial arts (e.g., kung fu, bagua) and/or mind–body practices (e.g., yoga, meditation).

Tai Chi naïve adults randomized to TC plus usual care or usual care alone were comparable at baseline (see **Table 1**). For all variables, values for the subset of participants that were found to be "per-protocol" were comparable to those in the larger sample thereby minimizing potential sources of bias in *post hoc* comparisons between control and TC compliant groups.

A CONSORT flowchart detailing study recruitment, randomization, and retention for the randomized trial component of the study is shown in **Figure 1**. Sixty healthy adults were successfully screened and enrolled, and 97% (28/29) and 87% (27/31) of individuals in the usual care and TC group completed the primary 6-month follow-up assessment, respectively.

Adherence to the TC protocol was variable. Two participants in the TC group formally withdrew participation due to time

TABLE 1 | Baseline characteristics.

	Randomized groups		Observational group
	Usual care ($n = 29$)	Tai Chi ($n = 31$)	Tai Chi experts ($n = 27$)
Age			
AVG ± SD	64.45 ± 7.42	63.94 ± 8.02	62.78 ± 7.57
Gender *n* (%)			
Male	11 (37.9%)	9 (29%)	13 (48.1%)
Female	18 (62.1%)	22 (71%)	14 (51.9%)
Race *n* (%)			
White	26 (89.7%)	29 (93.5%)	22 (81.5%)
African-American	3 (10.3%)	0 (0%)	1 (3.7%)
Asian	0 (0%)	2 (6.5%)	4 (14.8%)
Ethnicity *n* (%)			
Non-Hispanic/Non-Latino	29 (100%)	30 (96.8%)	26 (96.3%)
Hispanic/Latino	0 (0%)	1 (3.2%)	1 (3.7%)
Education (years)			
AVG ± SD	16.19 ± 3.03	17.13 ± 3.41	18.44 ± 3.34
Mini mental state exam (MMSE)			
AVG ± SD	29.21 ± 0.82	29.03 ± 1.17	29.07 ± 1.11
Trail making B (s)			
AVG ± SD	59.93 ± 20.84	59.69 ± 22.03	53.07 ± 22.4
Trail making B–A (s)			
AVG ± SD	29.54 ± 18.58	30.26 ± 20.01	28.09 ± 19.65
Body mass index (BMI; kg/m^2)			
AVG ± SD	26.54 ± 5.83	26.38 ± 5.19	23.54 ± 2.35[a]
Physical activity level[b]			
AVG ± SD	4.0 ± 2.0	4.0 ± 2.0	6.0 ± 2.0[a]

[a] *Cross-sectional comparisons between Tai Chi experts and Tai Chi naïve adults at baseline differed significantly ($p < 0.05$) in BMI and physical activity level.*
[b] *4 = Run about 1 mile/week OR walk about 1.3 miles/week OR spend about 30 min/week in comparable physical activity; 6 = run about 6–10 miles/week OR walk 7–13 miles/week OR spend 1–3 h/week in comparable physical activity.*

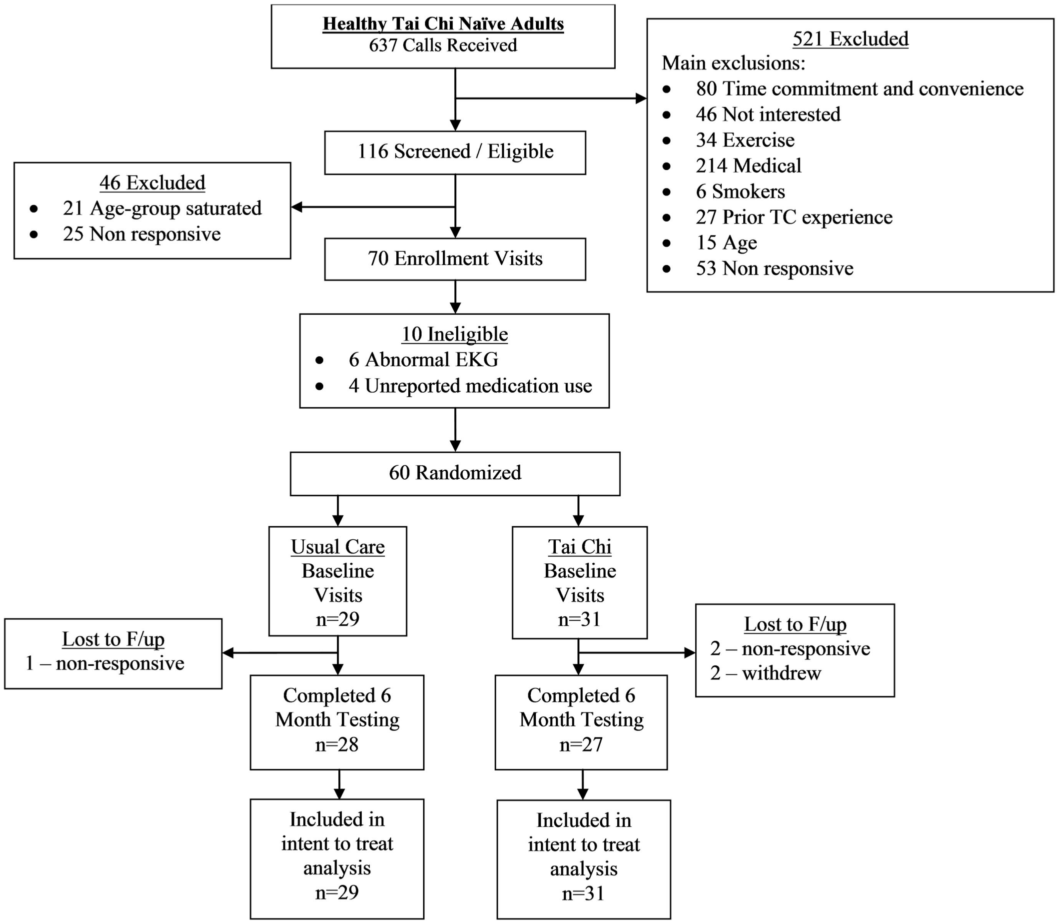

FIGURE 1 | Participant flow through the randomized trial sub-study.

commitments and an unrelated injury. Of the remaining 29 participants in the TC group, 21 (72%) were per-protocol – defined as attending 70% of classes and completing 70% of required home practice over the entire course of the trial (mean and median TC exposure hours were 59.9 and 62.4 h, respectively).

For those randomized to TC, 13 subjects were trained at a TC school teaching Yang style and the remaining 18 subjects were trained at a school teaching Wu style.

General Effects of Dual Task Challenges

Compared to undisturbed walking, gait speed decreased during DT walking in both TC expert ($p = 0.003$) and TC naïve ($p < 0.001$) adults. Stride time variability also increased with the addition of a DT in both TC expert ($p = 0.004$) and TC naïve ($p < 0.001$) adults (see **Table 2**).

Gait Performance in Tai Chi Experts vs. Tai Chi Naïve Older Adults

Linear models adjusting for variation due to age, gender, BMI, and activity revealed that average walking speeds were very similar in the TC naïve vs. TC expert groups during both undisturbed single task and DT walking. Group differences in these outcomes, as well as derived differences in absolute or percent DT costs, were not statistically significant (see **Table 2**; **Figure 2**). By contrast, stride time variability was lower in the TC expert vs. the TC naïve group, significantly so during DT walking (2.11 vs. 2.55%, respectively; $p = 0.027$). Absolute and percent DT costs of stride time variability also trended toward being lower in TC experts, but these differences were not statistically significant (recall **Table 2**). Of note, the two groups did not differ on performance of the serial subtractions during the DT walking trial. The number of serial subtractions attempted and their accuracy were 31 and 90%, respectively, in TC naïve group and 35 and 90%, respectively, in the TC expert group ($p = 0.81$). Age did not directly impact any gait variable, and treatment × age interactions for all cross-sectional comparisons were not statistically significant.

The Impact of Short-Term Tai Chi Training on Gait Performance

Random-slopes model with shared baseline adjusting for variation due to age, gender, BMI, and activity also revealed trends toward reduced stride time variability following 6 months of TC. A small improvement in DT stride time variability (effect size = 0.2) was estimated with TC training, but no significant differences between groups were observed (see **Table 3**). Potentially important improvements after TC training could not be excluded in

TABLE 2 | Cross-sectional comparison of gait parameters for Tai Chi expert and Tai Chi naïve older adults during undisturbed single task (ST) and dual task (DT) walking.

Outcome measure	Tai Chi expert ($n = 27$)	Tai Chi naïve ($n = 60$)	Between groups		
	Mean (95% CI)	Mean (95% CI)	Effect size	Mean difference (95% CI)	*p*-Value
Gait speed ST (m/s)	1.12 (1.1, 1.2)	1.12 (1.1, 1.2)	0.008	−0.001 (−0.08, 0.07)	0.97
Gait speed DT (m/s)	1.01 (1.0, 1.1)[a]	0.97 (0.9, 1.1)*	0.28	0.041 (−0.03, 0.1)	0.26
Stride time variability ST (CV %)	1.75 (1.5, 2.0)[b]	1.90 (1.8, 2.0)**	0.29	−0.15 (−0.4, 0.1)	0.25
Stride time variability DT (CV %)	2.11 (1.8, 2.4)	2.55 (2.3, 2.8)	0.57	−0.44 (−0.8, −0.5)	0.027
Abs. DT cost speed	−0.11 (−0.2, −0.1)	−0.15 (−0.2, −0.1)	0.34	0.042 (−0.02, 0.1)	0.18
% DT cost speed	−9.50 (−13.9, −5.1)	−13.24 (−16.1, −10.4)	0.34	3.74 (−1.7, 9.1)	0.17
Abs. DT cost variability	0.36 (0.03, 0.7)	0.65 (0.4, 0.9)	0.35	−0.29 (−0.7, 0.1)	0.16
% DT cost variability	23.49 (3.3, 43.7)	40.82 (27.7, 54.0)	0.35	−17.33 (−42.3, 7.6)	0.17

Means and 95% confidence intervals predicted from linear model adjusting for age, gender, BMI, and physical activity.
ST, single task; DT, dual task; CV, coefficient of variation.
[a]*Within-group comparisons between undisturbed and DT walking speed among Tai Chi experts ($p = 0.003$) and *Tai Chi naïve ($p < 0.001$).*
[b]*Within-group comparisons between undisturbed and DT walking stride time variability among Tai Chi experts ($p = 0.004$) and **Tai Chi naïve ($p < 0.001$).*

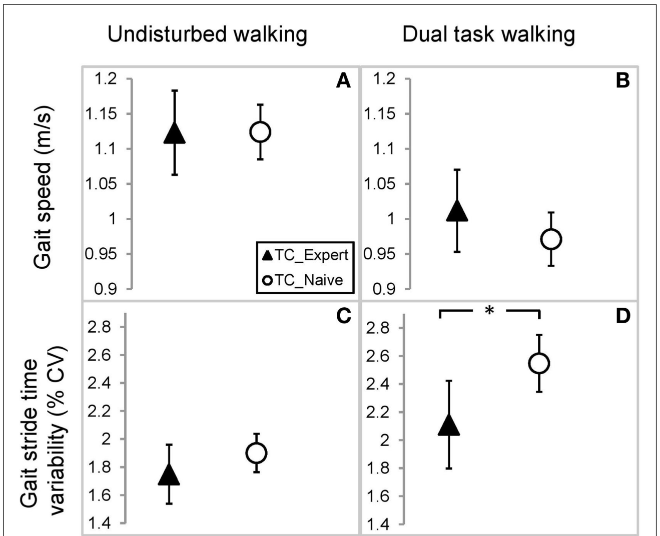

FIGURE 2 | Comparison of gait parameters between Tai Chi expert and Tai Chi naïve older adults. Estimated mean and 95% confidence intervals for gait speed during undisturbed **(A)** and dual task walking **(B)**, and gait stride time variability during undisturbed **(C)** and dual task walking **(D)**. Values based on a linear mixed model accounting for variations in age, gender, BMI, and physical activity. *Indicates $p < 0.05$.

this small study. The estimated 95% CI for DT stride time variability includes a 20% improvement from short-term TC training. Effects of TC on stride time variability during quiet walking were negligible (ES < 0.1).

Both the TC and usual care group increased DT walking speed ($p = 0.018$ and $p = 0.028$), but the difference between groups in changes over 6 months were not significant ($p = 0.94$). No within- or between-group differences were observed for single task walking speed (see **Table 3**). *Post hoc* per-protocol analyses (i.e., limited to participants that were TC compliant) did not substantially change within- and between-group observed patterns and trends. Changes over 6 months in absolute and percent DT costs for both gait speed and stride time variability were small and largely uninfluenced by treatment assignment (recall **Table 3**). As in the cross-sectional comparisons, these groups did not differ on performance of the serial subtractions. The number of serial subtractions attempted and their accuracy at the final 6-month visit was 33 (95%) in usual care group and 33 (92%) in the Tai expert group ($p = 0.58$). Age did not directly impact longitudinal changes in any gait variable, and treatment × age interactions for all outcomes were not statistically significant.

Discussion

To our knowledge, this study presents the first evidence that TC has the potential to positively impact DT stride time variability in healthy older adults. Cross-sectional comparisons revealed a significant degree of lower stride variability during dual tasking in TC experts, compared with TC naïve healthy older adults. Moreover, TC-naïve adults that were exposed to 6 months of TC training exhibited within-group significant improvements in DT stride time variability. By contrast, we observed limited impact of TC on stride variability during quiet walking or of TC on gait speed during single task walking.

As DT stride variability is associated with falls in the elderly (Visser, 1983; Nakamura et al., 1996; Hausdorff et al., 1997, 2001; Mbourou et al., 2003; Springer et al., 2006; Herman et al., 2010; Mirelman et al., 2012), the observed effect of TC on DT stride variability in this study may help to explain the positive effects of TC on fall risk reported in other studies (Logghe et al., 2010; Gillespie et al., 2012). Our results also suggest that DT stride variability may be a good discriminating metric for understanding the potential of TC to impact function in healthy and already active older adults. Finally, our findings support the value of research already underway to better understand the neurophysiological processes underlying how mind–body practices like TC impact cognitive–motor interactions (Li et al., 2014; Zheng et al., 2015).

Results of a recent 5-year prospective cohort study of healthy community-dwelling adults, ages 70–90 years and without gait impairments, provide context for the relevance of our findings. In adjusted models that accounted for age, gender, and fall history, baseline DT stride time variability (average CV was 2.97 ± 1.47%) was the only performance-based measure that predicted falls (Rate Ratio 1:11) (Mirelman et al., 2012). Although the DT stride variability in our relatively younger and healthier study population is

TABLE 3 | Longitudinal change in gait parameters for older adults randomly assigned to 6 months of Tai Chi vs. usual care during undisturbed single task (ST) and dual task (DT) walking.

Outcome measure	Tai Chi ($n = 31$)			Usual care ($n = 29$)				Between groups	
	Baseline	6 months	Within-group *p*-value	Baseline	6 months	Within-group *p*-value	Effect size	Mean difference (95% CI)	*p*-Value
	Mean (95% CI)	Mean (95% CI)		Mean (95% CI)	Mean (95% CI)				
Gait speed ST (m/s)	1.12 (1.1, 1.2)	1.16 (1.1, 1.2)	0.074	1.12 (1.1, 1.2)	1.17 (1.1, 1.2)	**0.032**	0.076	−0.011 (−0.07, 0.05)	0.71
Gait speed DT (m/s)	0.97 (0.9, 1.0)	1.03 (1.0, 1.1)	**0.018**	0.97 (0.9, 1.0)	1.03 (1.0, 1.1)	**0.028**	0.016	0.002 (−0.06, 0.06)	0.94
Stride time variability ST (CV %)	1.96 (1.8, 2.1)	1.74 (1.5, 2.0)	0.11	1.96 (1.8, 2.1)	1.79 (1.5, 2.0)	0.22	0.079	−0.044 (−0.3, 0.3)	0.77
Stride time variability DT (CV %)	2.58 (2.3, 2.9)	2.29 (2.0, 2.6)	**0.035**	2.58 (2.3, 2.9)	2.46 (2.2, 2.8)	0.39	0.19	−0.17 (−0.5, 0.1)	0.27
Abs. DT cost speed	−0.15 (−0.2, −0.1)	−0.14 (−0.2, −0.1)	0.63	−0.15 (−0.2, −0.1)	−0.14 (−0.2, −0.1)	0.65	0.002	0.0 (−0.06, 0.06)	0.99
% DT cost speed	−12.92 (−16.7, −9.2)	−11.32 (−15.0, −7.7)	0.43	−12.92 (−16.7, −9.2)	−11.33 (−16.0, −6.7)	0.52	0.001	0.014 (−5.4, 5.4)	>0.99
Abs. DT cost variability	0.62 (0.3, 0.9)	0.61 (0.3, 0.9)	0.95	0.62 (0.3, 0.9)	0.62 (0.3, 0.9)	0.98	0.007	−0.007 (−0.4, 0.4)	0.97
% DT cost variability	39.48 (20.9, 58.1)	38.00 (20.7, 55.4)	0.90	39.48 (20.9, 58.1)	40.13 (22.1, 58.2)	0.96	0.037	−2.13 (−23.8, 19.6)	0.85

Means and 95% confidence intervals predicted from shared baseline linear model adjusting for age, gender, BMI, and activity. No between-group comparisons (i.e., no tests of group × time interactions) were statistically significant. Within-group significant changes ($p < 0.05$) are highlighted in bold.
ST, single task; DT, dual task; CV, coefficient of variation.

moderately lower, we still found TC related improvements, with stride time variability decreasing by 11% following 6 months of TC training (from 2.58 to 2.29), and variability being 18% lower in TC experts vs. TC naives (2.11 vs. 2.58). These differences are clinically relevant and within a range that impacts future fall risk (Mirelman et al., 2012).

Prior studies evaluating the impact of TC on gait performance in older adults are quite variable in design and findings. We are not aware of any studies that evaluated the impact of TC on stride time variability and only a small number of studies have evaluated outcomes utilizing a DT paradigm. In one recent study of older adults (mean age 87.7 years) living in assisted living facilities, Manor et al. (2014) also reported an increase DT walking speed following 12 weeks of TC. However, unlike in our study, they also reported TC related increases in quiet walking speed. Our lack of an observed increase in quiet walking speed following TC parallels some other findings (Wolf et al., 2006; Zhang et al., 2006; Amano et al., 2013), although multiple studies have also reported TC-related increases in quiet walking speed (Yeh et al., 2004; Li et al., 2005; Shen et al., 2008; Li and Manor, 2010). Differences among these studies may be related to the age and health characteristics of the populations studied, and the different neuromuscular processes emphasized in different gait outcomes.

Our observed differences in outcomes based on stride time variability but not gait speed are not surprising. These features of gait have been shown to be independent and reflect different neuromotor processes (Hausdorff, 2005). Compared to gait speed, stride time variability reflects the control of the rhythmic stepping mechanism (Gabell and Nayak, 1984; Lord et al., 2013a), and has been characterized as an index of gait steadiness and control (Hausdorff et al., 1997, 2001; Verghese et al., 2009; Lord et al., 2013b). Inconsistency in gait rhythm, i.e., higher stride-to-stride variability, is a characteristic feature of gait in both Parkinson's disease (Hausdorff et al., 2003; Lord et al., 2011) and multiple sclerosis (Socie and Sosnoff, 2013). Studies demonstrating improved TC motor control during gait in adults support our findings of reduced variability, and thus dynamic postural control, following long- and short-term TC training. For example, a randomized trial of frail elders reported that TC training improved neuromuscular coordination and the mechanism by which forward momentum is generated during gait initiation (Hass et al., 2004). Another trial in patients with vestibular disorders showed that TC was associated with reorganized lower extremity neuromuscular patterns, which appear to promote a faster gait and reduce hip compensatory movements (McGibbon et al., 2005).

Our finding that the impact of TC on gait was more apparent during DT vs. undisturbed walking conditions was also consistent with our hypotheses. DT-related changes in gait may result from interference caused by a competition between the attention demanded by gait and the attention demanded by a concomitant task, in our case, serial subtractions recited aloud (Verhaeghen et al., 2002; Woollacott and Shumway-Cook, 2002). Therefore, DT interference reflects a condition of more limited attentional resources, and thus is a more provocative condition for evaluating the impact of an intervention than is quiet walking. Even healthy young adults' walk change their gait pattern under DT conditions (Srygley et al., 2009). Thus, we predicted that in the already active and healthy population of adults we studied, the impact of TC training would be most apparent in DT stride time variability, an outcome that challenges both the higher order process of gait rhythmicity and attentional competition. Our preliminary observations of both significant between-group differences in the comparison of TC experts vs. naives and within-group responses to 6 months of TC training, lends support to the hypothesis that TC enhances the attentional demands of walking. These findings also suggest that DT stride variability may be a sensitive and discriminating metric for evaluating the impact of interventions on cognitive–motor function in relatively healthy older adults. Other studies, including evaluations of cognitive–motor interactions in apparently asymptomatic prodromal Parkinson's patients, have also reported DT stride time variability to be a discriminating metric (Mirelman et al., 2011).

The potential of TC to reduce cognitive–motor competition is supported by other studies in which more challenging DT activities have better discriminated potential cognitive–motor benefits of TC. For example, in a randomized trial comparing short-term TC training to more traditional balance training, when exposed to simulated slips (experimentally shifted supporting force plates) older adults exposed to TC showed reduced tibialis anterior reaction time and reduced occurrence of co-contraction with antagonist muscles (Gatts and Woollacott, 2006, 2007). In another cross-sectional comparison of older adults TC practitioners and healthy controls, participants were asked to step down from a 19-cm high platform and maintain a single leg stance with and without a concurrent cognitive task (Lu et al., 2013). While the TC group maintained better postural control under all conditions, improved performance was magnified under the DT conditions. Other studies have also reported TC-related benefits for stepping tasks that included mental distractions (Wu, 2012), and walking performance on obstacle courses that require motor planning (Zhang et al., 2011). However, there are studies that have reported no benefit of TC for tasks which require executive function (Hall et al., 2009).

Limitations

Our study has a number of important limitations. First, samples for both the cross-sectional comparison and RCT were small, and could have resulted in type II errors. Because we considered this an exploratory study, we included statistical evaluations of outcomes without adjusting for multiple comparisons. When multiple comparisons were accounted for with Bonferonni adjustments, none of the outcomes were statistically significant. Findings in this study were intended to generate hypotheses to explore in future studies. Thus, the long- and short-term effects of TC on DT stride parameters in active healthy adults will need to be confirmed in larger, adequately powered studies. For our RCT, it is also possible that lack of more robust findings are due to the fact that 6 months of TC is insufficient training time to impact DT stride variability, and/or that more provocative DT challenges (e.g., more complex mental tasks and/or stride variability while negotiating turns or obstacles) are needed to observe any therapeutic impact of TC. Finally, our use of a non-active wait-list comparison group does not control for participant expectancy or psychosocial support afforded by participation in active TC programs. Future studies will require active comparison groups (e.g., alternative group exercise programs) that control for these factors.

With respect to our cross-sectional study, comparisons between TC experts and naïves may be confounded by differences between groups other than TC exposure. While linear models that included potential confounders (i.e., age, gender, BMI, physical activity) suggested an association with TC even after these factors were taken into account, other factors, including training in other martial arts could not be fully accounted for.

Another limitation of this study is lack of objective independent measures of proficiency in TC, which may have varied considerably especially in our expert TC group. In our cross-sectional comparison, TC experience among experts ranged from 10 to 50 years. A regression analysis indicated a slightly inverse relationship between years of training and DT stride variability, but this relationship was not statistically significant ($R^2 = 0.02$ and $p = 0.47$). Similarly, per-protocol analysis of DT stride variability revealed marginally greater effect sizes than intent-to-treat analyses, but this effect was still not statistically significant. Future studies might benefit from using independent measures of TC skill or proficiency [e.g., Rosengren et al. (2003)], which would help guide analyses of direct associations between TC-related skills and therapeutic benefits. Finally, while our use of a pragmatic approach that included the evaluation of multiple TC styles affords a high level of generalizability, variation between styles may add additional heterogeneity in outcomes, resulting in further reduced power for a given sample size (Macpherson, 2004).

Conclusion

In healthy active older adults, trends toward positive TC effects on gait were most obvious only under cognitively challenging DT conditions, and only for stride time variability. DT stride variability offers a potentially sensitive metric for monitoring the impact of TC on fall risk with healthy aging. These findings also support the value of neurophysiological research evaluating how mind–body exercises like TC impact cognitive–motor interactions and confirm previous findings, which suggest that TC reduces the risk of falls in older adults (Wolf et al., 1996; Gillespie et al., 2012). Future adequately powered studies are required to confirm these preliminary findings.

Author Contributions

PW, JH, LL, CP, and BM conceived and designed the study. ML acquired the study data with oversight from VN. ML and BG analyzed the study data. BG and EM performed statistical analysis. PW drafted and revised the manuscript. All authors reviewed the manuscript and approved the final version.

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Tai chi training reduces self-report of inattention in healthy young adults

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It is important to identify effective non-pharmacological alternatives to stimulant medications that reduce symptoms of attention deficit hyperactivity disorder (ADHD). In this study of healthy young adults, we measured the effects of training in tai chi, which involves mindful attention to the body during movement. Using a non-randomized, controlled, parallel design, students in a 15-week introductory tai chi course ($n = 28$) and control participants ($n = 44$) were tested for ADHD indicators and cognitive function at three points over the course of the 15-weeks. The tai chi students' self-report of attention, but not hyperactivity–impulsivity, improved compared to controls. At baseline, inattention correlated positively with reaction time variability in an affective go/no-go task across all participants, and improvements in attention correlated with reductions in reaction time variability across the tai chi students. Affective bias changed in the tai chi students, as reaction times to positive- and negative-valenced words equalized over time. These results converge to suggest that tai chi training may help improve attention in healthy young adults. Further studies are needed to confirm these results and to evaluate tai chi as therapy for individuals with ADHD.

Keywords: Tai chi, attention deficit disorder with hyperactivity, meditation, mindfulness, non-pharmacological intervention, college students, young adults

INTRODUCTION

The use of mind-body techniques to enhance cognitive function in young adults and adolescents would provide an attractive alternative to pharmacological treatment of conditions such as attention deficit hyperactivity disorder (ADHD), as well as non-medical use of stimulants for performance enhancement (Sussman et al., 2006; Krisanaprakornkit et al., 2010). Tai chi training may provide cognitive benefits to younger individuals as it has been shown to improve cognitive function in the elderly (Matthews and Williams, 2008; Man et al., 2010; Taylor-Piliae et al., 2010; Lam et al., 2012; Mortimer et al., 2012; Nguyen and Kruse, 2012; Lu et al., 2013). In this study we examine the effects of tai chi training on cognitive function in young adults.

Tai chi involves mindful attention to the body during a well-defined series of slow-flowing movements (Kauz, 1974; Jou, 1980). It is generally recognized as a safe and low-cost complementary therapy and is practiced by two million Americans for a variety of purposes (Barnes, 2004; Birdee et al., 2009). Recently, rigorous scientific methods have been applied to the study of the biomedical aspects of tai chi. While the purported health benefits of tai chi include psychological components, e.g., the cultivation of a state of relaxed attention, the majority of scientific studies focus on physical outcomes such as gait, posture, and cardiovascular health. These have largely examined middle-aged and elderly subjects (Wang et al., 2004a).

If tai chi were shown to improve attention in healthy subjects, it would provide support for future work to assess tai chi's efficacy as therapy for individuals with ADHD. ADHD affects 3–7% of children in the U.S. and persists into adulthood in 30–70% of cases (American Psychiatric Association, 2000; Lara et al., 2009). More than three million American patients with ADHD are treated with the stimulants amphetamine and methylphenidate, both of which target the dopamine transporter (Levy, 1991; Swanson et al., 2007). Brain imaging studies also suggest the dopamine system plays a role in ADHD (Durston, 2010). Medications are in some cases ineffective, poorly tolerated, or not desired (Kooij et al., 2010; Castells et al., 2011; Green and Rabiner, 2012). Therefore, non-pharmacological therapies are the subject of research (Toplak et al., 2008; Zylowska et al., 2008; Knouse and Safren, 2010; Krisanaprakornkit et al., 2010; Young and Amarasinghe, 2010). In a non-controlled study of 13 adolescent individuals with ADHD, teacher ratings of symptoms improved following a 5-week tai chi course (Hernandez-Reif et al., 2001). Moreover, teenagers who struggle with ADHD-like symptoms but do not meet full criteria for ADHD have been shown to be at increased risk for several psychiatric disorders (Malmberg et al., 2011), suggesting that non-pharmacological interventions for inattention and hyperactivity in healthy individuals may also be warranted.

Here we report an observational study comparing healthy young adults undergoing 15 weeks of tai chi training to a passive control group. The outcome measures were cognitive function, physical balance, and ADHD indicators, all measured at the beginning, middle, and end of the semester. Because spatial working memory (SWM) and response inhibition are associated with ADHD and respond to stimulant therapy, our primary *a priori* hypothesis was that, compared to controls, subjects in the tai chi course would show improvements in specific measures within these neurocognitive domains (Chamberlain et al., 2011). Given reports that ADHD patients exhibit greater reaction time (RT) variability (Tamm et al., 2012; Kofler et al., 2013), in *post hoc* analyses we examined correlations between RT variability and ADHD measures.

MATERIALS AND METHODS

SUBJECTS

Tai chi students were recruited from the University of Wisconsin-Madison course "Introduction to Martial Arts: Tai Chi" and were compensated $30. Control subjects were recruited from the UW course "Introduction to Psychology" and were compensated with course extra credit. Subjects were required to be between the age of 18 and 34 years, and there were no exclusion criteria. Recruitment and retention details are shown in **Table 1**, and participant demographics are presented in **Table 2**. The tai chi students were older than the control subjects (24.1 ± 3.5 vs. 19.4 ± 1.3 years), but otherwise there were no significant differences. All procedures were approved by the UW Social and Behavioral Sciences Institutional Review Board (SE-2012-0539), and the study was registered with ClinicalTrials.gov as a non-randomized trial (NCT01681082).

Table 1 | Recruitment and retention.

Number participating	Control subjects	Tai Chi students
Session 1	57	34
1 and 2 and 3	40	26
1 and 2 (not 3)	4	1
1 and 3 (not 2)	0	2
Included in analysis[a]	44 (77%)	28 (82%)

[a] *Participants were included in the analysis if they participated in test session 1 and at least one additional test session (2 or 3). One of the two tai chi students who participated at session 3 but not at session 2 provided incomplete ASRS data at session 3 and was therefore excluded from the analysis. Percentage indicates retention, i.e., number included in analysis/number participating in session 1.*

Table 2 | Participant demographics.

	Control subjects	Tai Chi students	p^e
n	44	28	
Sex (Female)	31 (70%)	16 (57%)	0.367
Age (mean ± SD)[a]	19.36 ± 1.27	24.14 ± 3.46	<0.001
ESL[b]	14 (32%)	6 (21%)	0.490
Mind-body[c]	17 (39%)	13 (46%)	0.683
Exercise (mean ± SD)[d]	51.2 ± 26.1	50.8 ± 35.6	0.952

[a] *At start of semester,* [b] *number of subjects reporting English as second language,* [c] *number of subjects reporting previous mind-body experience (mindfulness, meditation, yoga, etc.),* [d] *Godin leisure time questionnaire Weekly Leisure Activity Score.* [e] *p value for group difference, two sample t-test for age and exercise and chi-squared test for sex, ESL, and mind-body.*

INTERVENTION

Tai chi students attended 50 m classes twice per week for 15 weeks, with approximately 20 students in each class. The course emphasized experiential learning with three weeks of introductory sessions on gait, posture, and tai chi principles followed by instruction in the 24-form Yang style sequence (Qu, 1999). The course has been taught for over 10 years by the same instructor, who emphasizes the mindfulness aspect of tai chi. The instructor checked attendance at each class and after a fourth absence, the final grade was lowered by one-half grade for each additional absence. Control subjects were given no training or instructions.

PROTOCOL

All subjects underwent 1-h test sessions at the beginning, middle, and end of the 15-week semester to assess balance, cognitive function, and ADHD indicators. Testing was performed on one set of tai chi students and controls during Fall 2012 and on a second set during Spring 2013.

BALANCE MEASURE

Subjects performed the One-Legged Stance Test (OLST), in which they stood on one leg with eyes closed as long as possible for up to 60 s per trial (Briggs et al., 1989). The test was repeated alternately on both legs three times. The average of the best time on each leg was chosen *a priori* as the outcome measure.

COGNITIVE MEASURES

Participants performed three CANTAB® (Cambridge) computer button box- and touchscreen-based tests [CANTABeclipse(TM), 2012]. In the SWM test participants search for a token in a group of up to eight boxes without returning to boxes where a token had been found in a previous trial. In the Stop Signal Task (SST) subjects are instructed to rapidly press a left or right button depending on the direction of a stimulus arrow. On a subset of trials, an auditory stop signal indicates that the subject must inhibit their response. The presentation time of the stop signal is adjusted over the course of the test so the participant is able to withhold a button press in half of the stop trials. In the Affective Go/No-Go test (AGN) the participant is informed of both the target and distractor valence (positive, negative, or neutral) for a rapidly presented series of words and instructed to press a button for words of the target valence only. Outcome measures identified *a priori* were SWM "between errors" (primary outcome measure: number of times the subject revisited a box in which a token was previously found, i.e., "between" trials with the same pattern of boxes), SST stop signal RT (a response inhibition measure: mean go-trial RT minus mean stop signal presentation time, so lower values are better), and AGN correct RT (average over positive, neutral, and negative valenced words). Additional measures included affective bias (AGN correct RT, positive minus negative valenced words), AGN RT variability (mean over three valences of SD of correct response RT), and SST RT variability (SD of RT on go trials).

SELF-REPORT

Participants responded to four questionnaires: (1) Demographics: date of birth, sex, primary language, academic year and major, ethnicity, and race (first session only). (2) Adult ADHD Self-Report Scale (ASRS): 18 DSM-IV criteria as self-report Likert scale (0–4) items (Kessler et al., 2005). Of *a priori* interest was the sum score (0–24) from the six-question ASRS short screen consisting of inattention items 4, 5, 6, and 9 and hyperactivity–impulsivity items 1 and 5. In exploratory analysis, the two sub-scores (0–36) were evaluated for all nine inattention items and all nine hyperactivity–impulsivity items. (3) Experience with Mind-Body Practices: mindfulness, meditation, yoga, etc. (4) Godin Leisure-Time Exercise Questionnaire: frequency of strenuous, moderate, and mild exercise expressed as Weekly Leisure Activty Score (Godin and Shephard, 1985). In the Fall, subjects responded to paper versions of the questionnaires, while in the Spring, they responded to computer versions (Qualtrics). Additionally, the tai chi students were given a paper practice log and asked to keep a daily record of time spent practicing tai chi including class time; the log was collected at Session 2 and Session 3.

STATISTICAL ANALYSIS

Analyses were performed in R version 2.15.1 (R Development Core Team, 2012). Dependent variables were analyzed using a linear mixed effects model (LMER) with subject as a random effect and group and session as fixed effects. Effects of tai chi training were inferred from group × session interactions. Nuisance variables of age, sex, ESL, mind-body experience, and weekly leisure activity score were also included as fixed effects. Correlations between baseline scores and between change scores were evaluated by linear regression. Results with $p < 0.05$ were considered significant, and no corrections were applied for multiple comparisons (five a priori measures and four exploratory measures).

RESULTS

These results are based on data from 28 tai chi students and 44 control subjects. The tai chi students reported that they trained 101 ± 24 min per week. The effects of tai chi training were examined for the five quantities identified *a priori*, which provided specific measures of working memory, response inhibition, affective processing, physical balance, and the ADHD short screen. None of these measures exhibited significantly more change in the tai chi students compared to controls (**Table 3**). Changes from Session 1 to Session 3 in the affective go/no-go correct RT and the ADHD short screen were positively correlated across the tai chi students [$r(27) = 0.511$, $p = 0.006$]. There were no other correlations among changes in these five measures (remaining p's > 0.147), nor among these five measures at session 1 (all p's > 0.225).

Given the observed correlation in changes in the affective go/no-go correct RT and the ADHD short screen in the tai chi students, additional ADHD and affective go/no-go measures were explored (**Table 4**). As shown in **Figure 1**, inattention decreased by 10% relative to controls ($p = 0.044$, group × session interaction, no group difference at baseline), but there was no significant change in hyperactivity–impulsivity ($p = 0.748$). Analysis of the less attentive subjects in each group (median split at session 1, no group difference at baseline, data not shown) yielded a 16% reduction in the tai chi students' report of inattention compared to that seen in controls ($p = 0.002$). In the small number of participants whose baseline inattention score was above 20, the optimum threshold for concordance with clinician-rated ADHD classification (Kessler et al., 2005), tai chi students' self-report of inattention declined by 22% compared to controls ($p = 0.023$, tai chi $n = 3$, control $n = 4$, no group difference at baseline, data not shown). Although the reduction in affective go/no-go RT variability was not significantly different between the two groups ($p = 0.839$), the numerical value of the affective go/no-go bias measure (positive–negative correct RT) increased in the tai chi students compared to controls ($p = 0.008$ **Figure 2**).

Because RT variability has been proposed as a neurocognitive marker for ADHD (Tamm et al., 2012; Kofler et al., 2013), we explored correlations between the ADHD sub-scores for

Table 3 | Effect of tai chi training – measures specified a priori.

Mean (SEM)	Control subjects: Session 1	Control subjects: Session 2	Control subjects: Session 3	Tai Chi students: Session 1	Tai Chi students: Session 2	Tai Chi students: Session 3	Group × Session[f]: β	Group × Session[f]: *t*	Group × Session[f]: *p*
Working memory[a]	17.18 (2.86)	10.00 (1.48)	8.35 (1.29)	13.82 (2.48)	9.15 (1.82)	9.44 (1.59)	4.738	1.659	0.099
Physical balance (s)[b]	30.84 (2.95)	31.82 (2.76)	34.36 (3.06)	36.86 (3.55)	45.82 (3.17)	46.63 (3.26)	5.937	1.726	0.086
Response inhibition (ms)[c]	162.59 (6.25)	149.38 (6.15)	152.56 (6.95)	162.54 (7.92)	139.64 (6.34)	146.70 (7.05)	−3.289	−0.321	0.749
Affective processing (ms)[d]	493.88 (12.17)	510.09 (11.20)	520.30 (10.92)	523.58 (12.50)	539.41 (10.68)	538.30 (11.72)	−8.16	−0.928	0.355
ADHD short screen[e]	8.98 (0.47)	9.61 (0.55)	9.40 (0.52)	8.54 (0.53)	8.93 (0.53)	9.15 (0.43)	0.221	0.379	0.705
Day of semester, Mean (SD)	15.6 (7.4)	52.4 (5.8)	95.9 (3.8)	9.8 (5.8)	51.2 (7.5)	96.2 (3.9)			

Outcome measures identified a priori (clinicaltrials.gov NCT01681082). Measures from test sessions conducted at (1) beginning, (2) middle, and (3) end of semester. There were no significant differences between groups at baseline. [a] CANTAB spatial working memory task "between errors" (primary outcome measure), [b] One legged stance test, average across both legs of best trial, [c] CANTAB stop signal reaction time, [d] CANTAB affective go/no-go task mean correct RT, [e] ASRS 6 item short screening scale, [f] linear mixed effects model group × session interaction: β = change from session 1 to session 3 in tai chi students relative to controls, t = t value, p = 2-tailed p value.

Table 4 | Effect of tai chi training – ADHD and affective processing.

mean (SEM)	Control subjects			Tai Chi students			Group × session[f]		
	Session 1	Session 2	Session 3	Session 1	Session 2	Session 3	β	t	p
ADHD									
Inattention[a]	14.86(0.69)	15.64(0.72)	15.57(0.74)	14.57(0.89)	14.30(0.69)	13.89(0.68)	−1.42	−2.025	0.044*
Hyperactivity–impulsivity[b]	12.66(0.58)	12.59(0.64)	13.00(0.84)	10.61(0.68)	11.89(0.55)	11.30(0.55)	0.277	0.322	0.748
Affective processing (ms)[c]									
Bias[d]	−11.41(3.73)	−7.80(4.39)	−18.45(4.37)	−18.09(6.20)	1.03(4.85)	−1.60(3.78)	23.205	2.671	0.008*
RT variability[e]	113.59(3.80)	110.87(3.69)	111.33(3.36)	111.25(4.46)	104.99(3.68)	107.83(4.32)	−0.938	−0.203	0.839

*Measures from test sessions conducted at (1) beginning, (2) middle, and (3) end of semester. There were no significant differences between groups at baseline except for hyperactivity–impulsivity. [a]ASRS inattention items 1–9, [b]ASRS hyperactivity–impulsivity items 1–9 (significant difference between groups at session 1, $p = 0.027$), [c]CANTAB affective go/no-go mean correct RT, [d]positive–negative, [e]SD averaged over three valences, [f]linear mixed effects model group × session interaction: β = change from session 1 to session 3 in tai chi students relative to controls, t = t value, p = 2-tailed p value. *$p < 0.05$.*

inattention and for hyperactivity–impulsivity with RT variability in the SST and the affective go/no-go task (**Table 5**). As shown in **Figure 3**, at session 1, inattention correlated positively with affective go/no-go RT variability across all subjects [$r(72) = 0.251$, $p = 0.034$]. From session 1 to session 3, improvements in attention were correlated with reductions in affective go/no-go RT variability across the tai chi students [$r(27) = 0.387$, $p = 0.046$] but not across the control subjects [$r(40) = 0.073$, $p = 0.655$]. There was, however, no significant group difference between these correlations ($p = 0.20$). In addition, tai chi students who reported more practice time tended to exhibit greater reductions in affective go/no-go RT variability at a trend level [$r(27) = -0.320$, $p = 0.104$]. There were also correlations in unexpected directions of practice time with change in balance [$r(27) = -0.372$, $p = 0.056$] and change in the ADHD hyperactivity–impulsivity sub-score [$r(27] = 0.397$, $p = 0.040$].

DISCUSSION

We examined the effects of tai chi training on selected attentional and cognitive processes in healthy young adults, and found a reduction in self-reported inattention that was supported by neurocognitive measures. These results suggest tai chi training might serve as therapy for young adults and adolescents suffering from ADHD inattention symptoms. Additional results pointed to the potential sensitivity of emotional processing measures to tai chi training.

Attention deficit hyperactivity disorder inattention indicators decreased in tai chi students, and the improvements in attention correlated with reductions in RT variability in an affective go/no-go task. Reviews of the literature suggest RT variability may be a marker of ADHD (Tamm et al., 2012; Kofler et al., 2013). Indeed, in addition to the correlated changes seen in the tai chi students, affective go/no-go RT variability correlated with inattention across all subjects at baseline. These improvements in attention observed in healthy young adults lend credence to the notion that tai chi training might serve as an effective therapy for adolescents and young adults with ADHD. Encouragingly, in less attentive subsets of subjects from each group, whose attention scores were equivalent at baseline, the tai chi students exhibited greater reductions in inattention compared to controls. However, while self-report of inattention decreased significantly compared to controls, there was no significant change in self-report of hyperactivity–impulsivity. To our knowledge, the only report of tai chi as therapy for ADHD describes a single-arm study of 13 adolescent patients, in which teacher report of symptoms declined after 5 weeks of training (Hernandez-Reif et al., 2001). The present results underscore the potential of tai chi training and indicate the need for additional studies in ADHD patients.

Beyond the observed reduction in self-report of inattention and associated reductions in affective go/no-go RT variability, the present study yielded additional interesting results. Affective bias increased in the tai chi students as the rates of response to positive and negative words tended to equalize. Among the measures identified *a priori* the only significant result was the correlation in changes in the ADHD six-question screen and affective go/no-go RT. This correlation was echoed by the correlation seen between the ADHD inattention score and the affective go/no-go RT variability. Contrary to our *a priori* hypotheses, we actually observed a trend-level decline in the tai chi students' performance of the spatial working memory task compared to controls, and no significant improvement was observed in the SST measure of response inhibition. Analyses of dose effect, i.e., correlations of change in outcome measures with practice time, present a complex picture and suggest the need for more accurate measures of time spent practicing tai chi. Physical balance improved in the tai chi subjects compared to the controls, but only at trend level. It is also noteworthy that in the stop signal task measure of response inhibition, correlations between ADHD measures and RT variability, though not significant, were in the same direction as those seen in the affective go/no-go task, i.e., reduced RT variability was associated with improved ADHD indicators. Taken together, these additional results suggest measures of affective processing may be sensitive to tai chi training.

These results contribute to a small but growing body of literature describing the effects of tai chi training in healthy young adults. This literature suggests that tai chi training may lead to improvements in self-report of physical and mental health

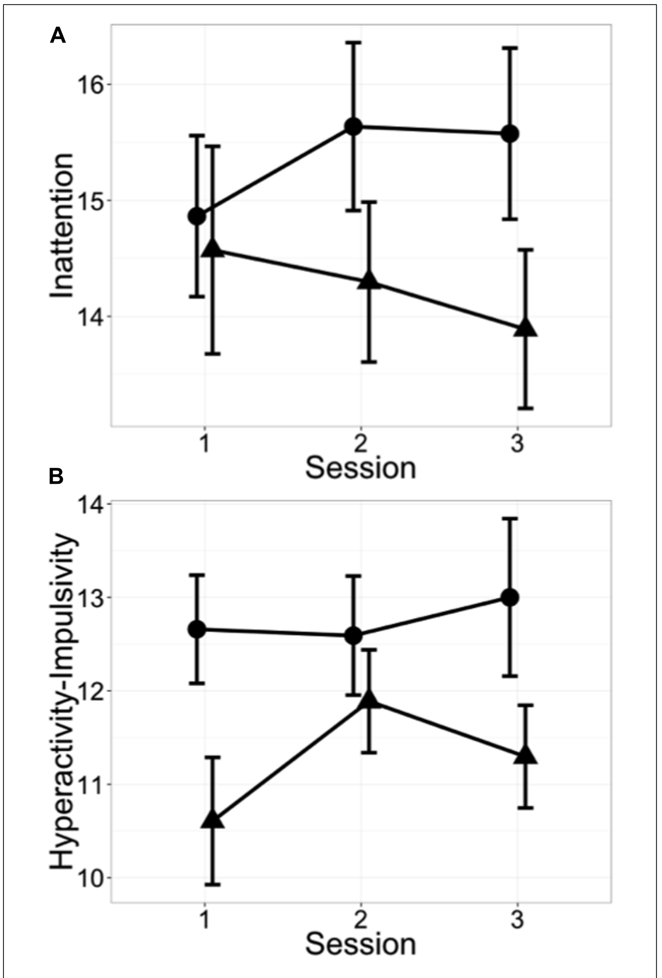

FIGURE 1 | Inattention, but not hyperactivity–impulsivity, was reduced in tai chi students compared to control subjects. (A) ADHD indicators of inattention (ASRS inattention items 1–9) improved in tai chi students relative to controls ($p = 0.044$, linear mixed effects model group × session interaction). **(B)** No significant change was seen in hyperactivity–impulsivity (ASRS hyperactivity–impulsivity items 1–9). Test sessions conducted at (1) beginning, (2) middle, and (3) end of semester. • = control subjects; ▲ = tai chi students. Mean ± SEM.

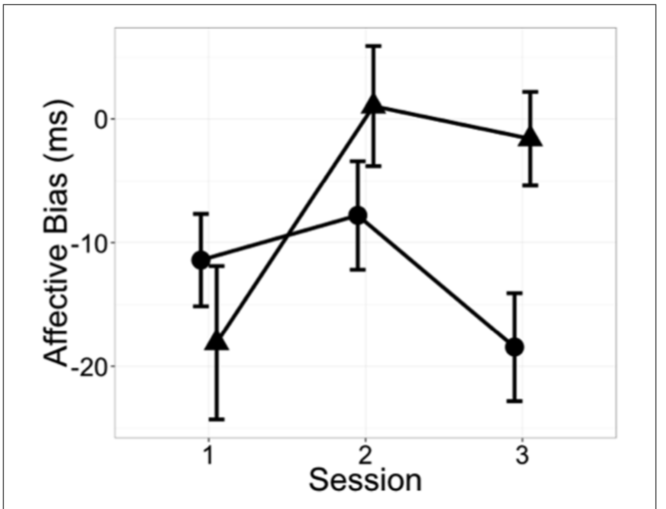

FIGURE 2 | Affective bias changed in tai chi students compared to control subjects. Specifically, reaction times to positive and negative valenced words tended to equalize in tai chi students over time ($p = 0.008$, linear mixed effects model group x session interaction). Test sessions conducted at (1) beginning, (2) middle, and (3) end of semester. • = control subjects; ▲ = tai chi students. Mean ± SEM. Bias = positive valence reaction time–negative valence reaction time.

Table 5 | Correlations between ADHD subscores and reaction time variability: at baseline and change over time.

Pearson *r*	**All subjects baseline**[g]	**Control Δ**[h]	**Tai Chi Δ**[h]
Inattention[a] **vs**			
Stop signal task[c]	0.137	0.227	0.217
Affective go/no-go[d]	0.251*[e]	0.073	0.387*[f]
Hyperactivity–impulsivity[b] **vs**			
Stop signal task	0.077	−0.026	−0.175
Affective go/no-go	0.108	−0.058	−0.104
n[i]	72	40	27

[a]*ASRS inattention items 1–9;* [b]*ASRS hyperactivity–impulsivity items 1–9;* [c]*CANTAB stop signal task, SD of reaction time over go trials;* [d]*CANTAB affective go/no-go task, correct RT SD averaged over 3 valences;* [e]*$p = 0.034$;* [f]*$p = 0.046$;* [g]*correlation between measures at session 1;* [h]*correlation between changes from session 1 to session 3;* [i]*session 3 data was unavailable for four control subjects and one tai chi student. *$p < 0.05$.*

measures (Wang et al., 2004b), decreased nightmares (Slater and Hunt, 1997), improvements in self-report of mindfulness, mood, perceived stress, and sleep quality (Caldwell et al., 2011), reductions in salivary cortisol as well as improvements in self-report of mental health measures and perceived stress (Esch et al., 2007), and improvements in measures of blood plasma immunological markers (Wang and An, 2011). Collectively, this literature suggests tai chi training in young adults may have salutary effects on mental health, perceived stress, and immune function. This literature also points to the need for more randomized controlled trials with objective measures of cognitive function.

The present study was strengthened by its interventional design, which, as opposed to a cross-sectional comparison of experienced and naive practitioners, permits inference of causality due to tai chi training. The use of a comparison group accounted for practice effects in testing. An additional strength was the use of objective neurocognitive measures. This study also had a number of limitations. The main findings resulted from exploratory analyses that do not survive multiple comparison correction, and they will require replication. It would be of particular interest to repeat the measures of inattention, RT variability, and affective bias. Although we used a control group, this was an observational study without randomization, so self-selection biases may exist. Mean age differed between the groups, although age was included as a nuisance variable in the linear mixed effects model. Because participants were aware that the purpose was to measure the psychological effects of tai chi training, demand characteristics may have influenced the

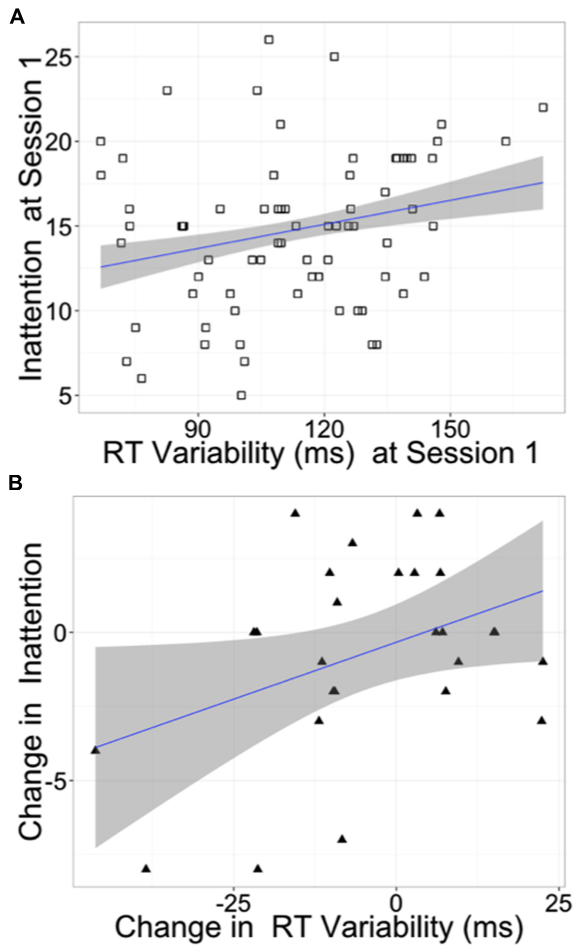

FIGURE 3 | Inattention and reaction time variability. (A) At baseline, inattention correlated with reaction time variability in the affective go/no-go task across all subjects [$r(72) = 0.251$, $p = 0.034$], and **(B)** improvements in attention correlated with reductions in reaction time variability across the tai chi subjects [$r(27) = 0.387$, $p = 0.046$]. Change from session 1 to session 3. Inattention: ASRS inattention items 1–9. Reaction Time (RT) Variability: mean over three valences of affective go/no-go correct RT SD.

results, although the reduction in self-report of ADHD indicators was supported by the objective RT variability measures. Researchers were aware of the subjects' group status and may therefore have introduced bias in their administration of the tests. Because a single experienced teacher provided tai chi instruction, generalizability is limited. Finally, we did not assess potentially confounding medical or recreational drug use. Future studies of cognitive effects of tai chi training will ideally be randomized controlled trials with an active control intervention to balance the social and physical aspects of tai chi along with assessment of confounding variables including participant expectations.

In conclusion, the results of this study in healthy young adults suggest that tai chi training improves attention and may therefore hold potential as a non-pharmacological intervention for individuals with ADHD. Additional studies are needed to confirm these results in healthy subjects and to extend this research to ADHD patient populations.

AUTHOR CONTRIBUTIONS

Alexander K. Converse developed the study concept. Alexander K. Converse, Elizabeth O. Ahlers, and Richard J. Davidson contributed to the study design. Testing and data collection were performed by Alexander K. Converse. Alexander K. Converse and Brittany G. Travers performed the data analysis and interpretation. Alexander K. Converse drafted the paper. Brittany G. Travers and Richard J. Davidson provided critical revisions. All authors approved the final version of the paper for submission.

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The Effects of Tai Chi Practice on Intermuscular Beta Coherence and the Rubber Hand Illusion

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Tai Chi (TC) is a slow-motion contemplative exercise that is associated with improvements in sensorimotor measures, including decreased force variability, enhanced tactile acuity, and improved proprioception, especially in elderly populations. Here, we carried out two studies evaluating the effect of TC practice on measures associated with sensorimotor processing. In study 1, we evaluated TC's effects on an oscillatory parameter associated with motor function, beta rhythm (15–30 Hz) coherence, focusing specifically on beta rhythm intermuscular coherence (IMC), which is tightly coupled to beta corticomuscular coherence (CMC). We utilized electromyography (EMG) to compare beta IMC in older TC practitioners with age-matched controls, as well as novices with advanced TC practitioners. Given previous findings of elevated, maladaptive beta coherence in older subjects, we hypothesized that increased TC practice would be associated with a monotonic decrease in beta IMC, but rather discovered that novice practitioners manifested higher beta IMC than both controls and advanced practitioners, forming an inverted U-shaped practice curve. This finding suggests that TC practice elicits complex changes in sensory and motor processes over the developmental lifespan of TC training. In study 2, we focused on somatosensory (e.g., tactile and proprioceptive) responses to the rubber hand illusion (RHI) in a middle-aged TC group, assessing whether responses to the illusion became dampened with greater cumulative practice. As hypothesized, TC practice was associated with decreased likelihood to misattribute tactile stimulation during the RHI to the rubber hand, although there was no effect of TC practice on measures of proprioception or on subjective reports of ownership. These studies provide preliminary evidence that TC practice both modulates beta network coherence in a non-linear fashion, perhaps as a result of the focus on not only efferent motor but also afferent sensory activity, and alters tactile sensations during the RHI. This work is the first to show the effects of TC on low level sensorimotor processing and integrated body awareness, and this multi-scale finding may help to provide a mechanistic explanation for the widespread sensorimotor benefits observed with TC practice in symptoms associated with aging and difficult illnesses such as Parkinson's disease.

Keywords: Tai Chi, beta rhythm, intermuscular coherence, EMG, body awareness, rubber hand illusion, embodiment

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INTRODUCTION

A growing number of studies have reported that mindfulness meditation elicits health benefits, including enhanced attentional processing (Jha et al., 2007; MacLean et al., 2010), cognition (Jha et al., 2010; Mrazek et al., 2013), and sensory processing (Mirams et al., 2013). An important feature of mindfulness is the cultivation of somatically directed attention, as individuals are instructed to attend to their sensory experience, such as the sensations of the flow of the breath (Kerr et al., 2013). In tandem with these behavioral findings, previous work from our lab and others has demonstrated that training in mindfulness leads to enhanced attentional control over excitability in the primary somatosensory cortex map of the body, as indexed by dynamic control over alpha (7–14 Hz) rhythms in this region (Kerr et al., 2011).

Tai Chi (TC) is a less well studied contemplative exercise in which practitioners cultivate attention to body sensations during slow movement and static warm-up postures (Wayne and Fuerst, 2013). Derived from a longstanding Chinese martial arts practice, TC is associated with enhancements in both motor and sensory domains, especially in elderly populations. In addition to improved balance and decreased fall risk in the elderly (Wolf et al., 1997; Schleicher et al., 2012), reduced force variability during complex motor tasks (Christou et al., 2003), and efficacy in reducing symptoms related to Parkinson's disease (Li et al., 2012), TC also trains somatosensory perceptual capacities such as proprioception (Li et al., 2008) and tactile acuity in the fingertip (Kerr et al., 2008) and the foot (Richerson and Rosendale, 2007).

Given TC's emphasis on somatic attention during movement, the observed benefits associated with the practice, and considering our previous finding that mindfulness modulates somatosensory alpha oscillations, here we sought to investigate the effects of TC practice on a sensorimotor parameter, beta (15–30 Hz) oscillatory rhythm coherence, that is related to the sensorimotor alpha rhythm recorded over sensorimotor cortex (Jones et al., 2009).

The beta band signal descending from motor cortex to the muscles is thought to play a causal role in synchronizing neural activity both across cortex and the muscles (Engel and Fries, 2010). This signal is referred to as beta corticomuscular coherence (CMC). The signal can also be captured intermuscularly, in recordings of opponent muscles involved in a static, isometric task (i.e., beta intermuscular coherence, IMC; Kilner et al., 1999; Baker, 2007). Beta CMC/IMC coherence during an isometric task is thought to temporally align the muscles and regulate force variability (Witte et al., 2007). In fact, beta CMC has been found to be inversely correlated with force variability (Johnson and Shinohara, 2012) in normal-aged subjects. However, in aging populations, beta CMC becomes over-expressed and loses its functional relationship to force variability (Johnson and Shinohara, 2012). In other words, although the descending beta CMC signal seems to serve a motor function of reducing force variability in younger populations, this functionality is absent in elderly populations as a consequence of becoming chronically elevated. A further complexity arises from the fact that in a small number of studies beta CMC has been associated with the afferent flow of proprioceptive information from the muscles to the cortex (Baker et al., 2006), although the functional significance of this finding remains unclear.

Given that beta IMC is tightly coupled with beta CMC (van Ede and Maris, 2013), here we evaluated the effects of TC practice on beta IMC. We hypothesized that TC practice, which has demonstrated sensory and motor benefits in the elderly, would reduce maladaptive age-related increases in muscle network coherence in a population of elderly TC practitioners. Furthermore, we hypothesized that this reduction in beta IMC in a sample of elderly TC practitioners would restore the inverse relationship between force variability and beta coherence found in younger populations. To test these hypotheses, we recorded beta IMC during a low force isometric task in a group of elderly TC practitioners and age-matched elderly controls.

As an exploratory extension of the primary study, we also investigated the effect of TC practice on the rubber hand illusion (RHI), a paradigm designed to test multi-sensory integration via experimental manipulation of visual, tactile, and proprioceptive streams of information (Botvinick and Cohen, 1998). In brief, the RHI involves an experimenter synchronously or asynchronously stroking both the real hand of the subject which is hidden from view, as well as a fake rubber hand placed in front of the subject in clear view. Often, subjects report experiencing altered tactile sensations, as if the sensations were originating from the strokes seen on the rubber hand, and numerous studies report that during the RHI, somatosensory processing is altered (Moseley et al., 2008; Zopf et al., 2011; Zeller et al., 2015). In addition, behavioral measures such as proprioceptive drift, which measures the distance from the perceived location of one's hand to its actual location, have indicated that the illusion induces a perceptual bias toward the concealed, rubber hand [although this phenomena is not always reproducible (Rohde et al., 2011; Abdulkarim and Ehrsson, 2015)].

Beyond tactile and proprioceptive components of the illusion, the RHI is widely used to study body-ownership and multi sensory processing underlying perception of one's own-body in healthy [see review (Kilteni et al., 2015)], as well as clinical populations [e.g., eating disorders (Eshkevari et al., 2012), schizophrenia (Thakkar et al., 2011), and chronic pain (Moseley et al., 2012)]. Given the phenomenological reports in the TC literature of changes in practitioners in the experience of embodiment (Wayne, 2013), we specifically utilized the RHI to investigate long term effects of TC practice on tactile and proprioceptive changes associated with the practice as well as embodiment as in (Longo et al., 2008b). We hypothesized that since TC practice enhances tactile acuity (Kerr et al., 2008) and improved tactile acuity is associated with decreased misattribution of tactile sensations to the fake rubber hand (Longo et al., 2008a), the TC practitioners in our sample will more accurately be able to attribute tactile sensations to the real arm. Furthermore, because TC enhances proprioception (Li et al., 2008; Longo et al., 2008a), we expected the TC practitioners in our sample to more accurately identify their hand position and thus show decreased proprioceptive drift. In addition, we hypothesized that this decreased perceptual error in tactile acuity and proprioception would result in a reduction of

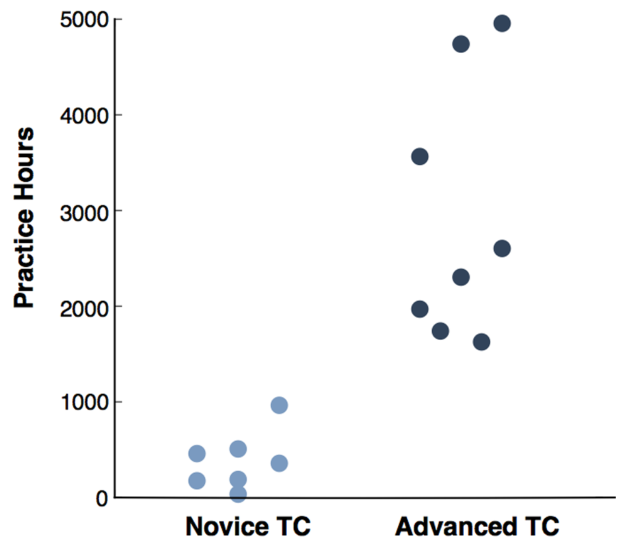

FIGURE 1 | The distribution of TC subjects' cumulative hours of practice experience: the seven subjects whose cumulative hours fall below 1000 h (a measure which multiple studies of contemplative practice (Taylor et al., 2011; van Vugt, 2015; Zeidan, 2015) have used to divide novice from advanced practitioners) were considered novice TC, and the remaining eight practitioners were considered advanced TC.

perceived illusory ownership of the rubber hand, as this aspect of the illusion arises from a multisensory integration of vision, proprioception, and touch. Note: the sample of TC practitioners in study 2, recruited from the same TC studio as study 1, was composed of a significantly younger ($p < 0.002$) cohort of practitioners (64.3 ± 4.7 in study 1; 51.5 ± 14.1 years in study 2).

An important prospective design consideration for both experiments was to consider the effect of cumulative practice experience (measured as self-reported hours of practice). Previous studies have shown cumulative practice can have significant effects on both neural (Brefczynski-Lewis et al., 2007) and behavioral sensorimotor parameters (Fox et al., 2012), especially in a group such as the present sample in which there exists considerable variability in practice experience (**Figure 1**). Therefore, for study 1, we considered novice and advanced practitioners as separate groups in order to hypothesize that we would see a monotonic decrease in beta IMC with increasing experience: controls > novice > advanced (see methods for our description of criteria used to divide the TC group into novice vs. advanced TC).

For study 2, hypotheses were constructed in light of a recent study showing no effect of an embodied contemplative practice (Yoga) on the RHI (David et al., 2014). Importantly, this null finding did not consider the effect that wide variance in practice experience among the Yoga practitioners (1.5–12 years) might have had on statistical tests of between group differences. In the current investigation, rather than evaluating the difference between a control group and the TC practitioner group, the study tested correlation between cumulative TC practice hours and subjective and objective responses to the RHI. Moreover, rather than evaluating the effects of practice on the overall subjective response to the RHI, the study focused more narrowly on specifically hypothesized sub-components of the RHI response, looking specifically at the tactile and proprioceptive questionnaire items (e.g., **Table 1**, items #1 and #4) in addition to the questionnaire item related to subjective ownership responses to the illusion (**Table 1**, item #3). We hypothesized that cumulative TC practice would be associated with (1) reduced responsiveness to a subjective tactile RHI question ("How much does it seem that the touch you are feeling is where you see the rubber hand being stroked?") (2) greater accuracy in proprioceptive judgment of the real arm through reduced objective measures of proprioceptive drift and reduced responsiveness to the subjective proprioception RHI question ("How much does it seem as though you are losing sense of where your own hand is?") and (3) reduced perceived ownership of the rubber hand as determined by responsiveness to the subjective ownership RHI question ("How much does it seem as though the rubber hand is your hand?"). A positive finding would suggest that over time, TC teaches practitioners to maintain connection to tactile/proprioceptive bodily sensations in a manner that may inhibit visual body illusions (e.g., the RHI).

MATERIALS AND METHODS

Study 1: Force Variability and Beta IMC

Subjects

Fifteen TC practitioners (64.3 ± 4.7 years, 9 female) from the Brookline Tai Chi studio [Brookline, MA, see (Frantzis, 2006) for details] and 16 control subjects (61.1 ± 6.0 years, 8 female) from the greater Boston, MA and Providence, RI communities were recruited to take part in this study (see **Figure 1**). Subjects were matched for age ($p > 0.05$) and education ($p > 0.05$) and were all right handed. Exclusion criteria for all subjects included the following: chronic arm, wrist, or hand pain in the last 2 years, any other movement or rheumatoid disorder, or recent muscle sprain to the hand, wrist, arm, or shoulder. TC practitioners must have maintained practice for at least three times per week for 12 months. This study was carried out in accordance with the

TABLE 1 | Five-item questionnaire derived from (Longo et al., 2008a; Jenkinson et al., 2013) to probe subjective aspects of the RHI.

Rubber Hand Illusion Questionnaire
(1) How much does it seem that the touch you are feeling is where you see the rubber hand being stroked?
(2) How much does it seem as if you might have more than one left hand?
(3) How much does it seem as though the rubber hand is your hand?
(4) How much does it seem as though you are losing the sense of where your own hand is?
(5) How much does it seem as though you are losing the sense of owning your hand?

Subjects respond with a number from 0 to 6 in response to the question, with lower numbers indicating negative responses and greater numbers indicating positive responses. Study hypotheses focused on TC practitioner responses to the tactile (Q1), ownership (Q3), and proprioceptive (Q4) questionnaire items.

recommendations of the Institutional Review Board at Brown University with written informed consent from all subjects. All subjects gave written informed consent in accordance with the Declaration of Helsinki.

Paradigm

Subjects were seated and asked to rest their right hand on a padded surface. Using their right thumb and index finger, subjects were instructed to apply a pinch grip onto a pair of compliant levers (compliance of 0.0167 N/mm) from a custom-built spring loaded lever grip device that included a load cell (A201 series FlexiForce Sensors, Tekscan, Inc. Boston, MA, USA).

In the task, subjects were directed to maintain a low force precision grip of 2 ± 0.03 N to the best of their ability for six separate 40-s trials while being provided with real time visual feedback of their applied force on a computer monitor. In three of the six trials, subjects were asked to attend to the sensory experience of their thumb and index finger, and in the remaining trials no explicit instructions were given (Note: one serious limitation of this approach was that there was no measurement of the efficacy of the subject's attentional shift). Time was kept by an experimentalist, and all trials were monitored for performance. Trials with significant fluctuations in force were excluded in the analysis. Subjects were also initially granted one practice trial to become familiar with the task. An example of the force trace can be seen in **Figure 2**.

Recordings

Surface electromyography (EMG) was recorded from the first dorsal interosseous (FDI) and the abductor pollicis brevis (AbPB) muscles of the right hand. The electrodes were placed on the belly of each muscle and placement accuracy was assessed using visual inspection of the raw output. EMG signals were amplified and band-pass filtered at 1–200 Hz. Both the EMG and the force readings were digitized with an analog-to-digital converter (Labchart, AD Instruments) at 1,000 samples/s. Prior to analysis, EMG signals and force readings were notch filtered at 60 Hz. Sample EMG traces can be seen in **Figure 2**.

Median Split of TC Group into Novice and Advanced Practitioners

An important part of our analysis was to consider prospectively the effects of cumulative TC experience on beta IMC. The basis of this focus on experience comes from several previous studies reporting significant differences even within training groups, specifically between novice and advanced practitioners. This suggests that a simple comparison between controls and TC practitioners would obscure potential relationships. A single test comparing controls, novice practitioners, and advanced practitioners allows us to evaluate both the effects of differences between TC and controls as well as between novice practitioners and advanced practitioners, while at the same time minimizing the number of required statistical tests.

Therefore, the study used a median split to divide the TC group in half in order to test the effect of practice (see **Figure 1**). A simple division of subjects into three groups (controls, novice TC practitioners, and advanced TC practitioners) allowed us to evaluate the effects of TC practice in relation to two questions: (1) do novice TC practitioners manifest lower beta IMC than controls? and (2) do advanced TC practitioners manifest lower beta IMC than novice TC practitioners?

As there were an odd number of TC subjects ($n = 15$), we took a principled approach to setting the parameters of the median split. The distribution of subject hours showed that the seven subjects with lowest hours fell well below 1000 h, which is a cut-off that multiple studies of contemplative practice (Taylor et al., 2011; van Vugt, 2015; Zeidan, 2015) have identified as an important cut point separating two distinct, differentiable groups (i.e., novices vs. advanced). By contrast, the next highest subject (subject 8) reported 1626 practice hours. Thus, based on the principle that expertise emerges in practitioners with more than 1000 h of practice, the TC group was split into seven novice practitioners and eight advanced practitioners.

Analysis

To carry out the analysis, beta IMC and force variability were computed for each of the three groups: controls ($n = 16$), novice practitioners ($n = 7$), and advanced practitioners ($n = 8$). Data from the six trials of each subject were concatenated together as no significant inter-trial differences were observed between baseline and attention trials, and the magnitude-squared-coherence between the FDI and AbPB signals was calculated using the equation and statistical significance commonly described in the literature (Halliday et al., 1995; Terry and Griffin, 2008). Specifically, a 1024 sample window (frequency resolution = 0.977 Hz), Hanning taper, and 50% overlap were used on de-trended and rectified EMG signals (see **Figure 2** for EMGs and peak beta IMC for typical subjects in each group). Peak coherence values in the beta band (15–30 Hz) were obtained as arc hyperbolic tangent transformed as in (Halliday et al., 1995; Johnson and Shinohara, 2012).

Force variability was calculated as the root mean square of the absolute difference between the subject's applied force and the constant 2 N target force as in (Witte et al., 2007). This measure provides a reliable indicator of the error between the target force and the applied force, and therefore a measure of the variability with which subjects could maintain a static hold.

Because of the study's small sample sizes all statistical tests were performed using non-parametric statistics as suggested by Mehta and Patel (1999). A further rationale for non-parametric tests comes from the fact that beta IMC has a highly non-normal distribution (determined in our sample with the Lilliefors test), as is commonly observed in the literature (Kilner et al., 1999; Johnson and Shinohara, 2012). Thus, the non-parametric Kruskal–Wallis test was used to compare beta IMC and force variability in controls, novice practitioners, and advanced practitioners (see **Figure 3**). The Spearman correlation coefficient was used to assess the relationship between force variability and beta IMC (see **Figure 4**). Because an important element of our hypothesis concerns the difference in the relationship between beta IMC and force variability in TC versus control subjects, we also evaluated the difference between Spearman correlation coefficients between the two groups in their respective correlations of beta IMC and force variability using procedures

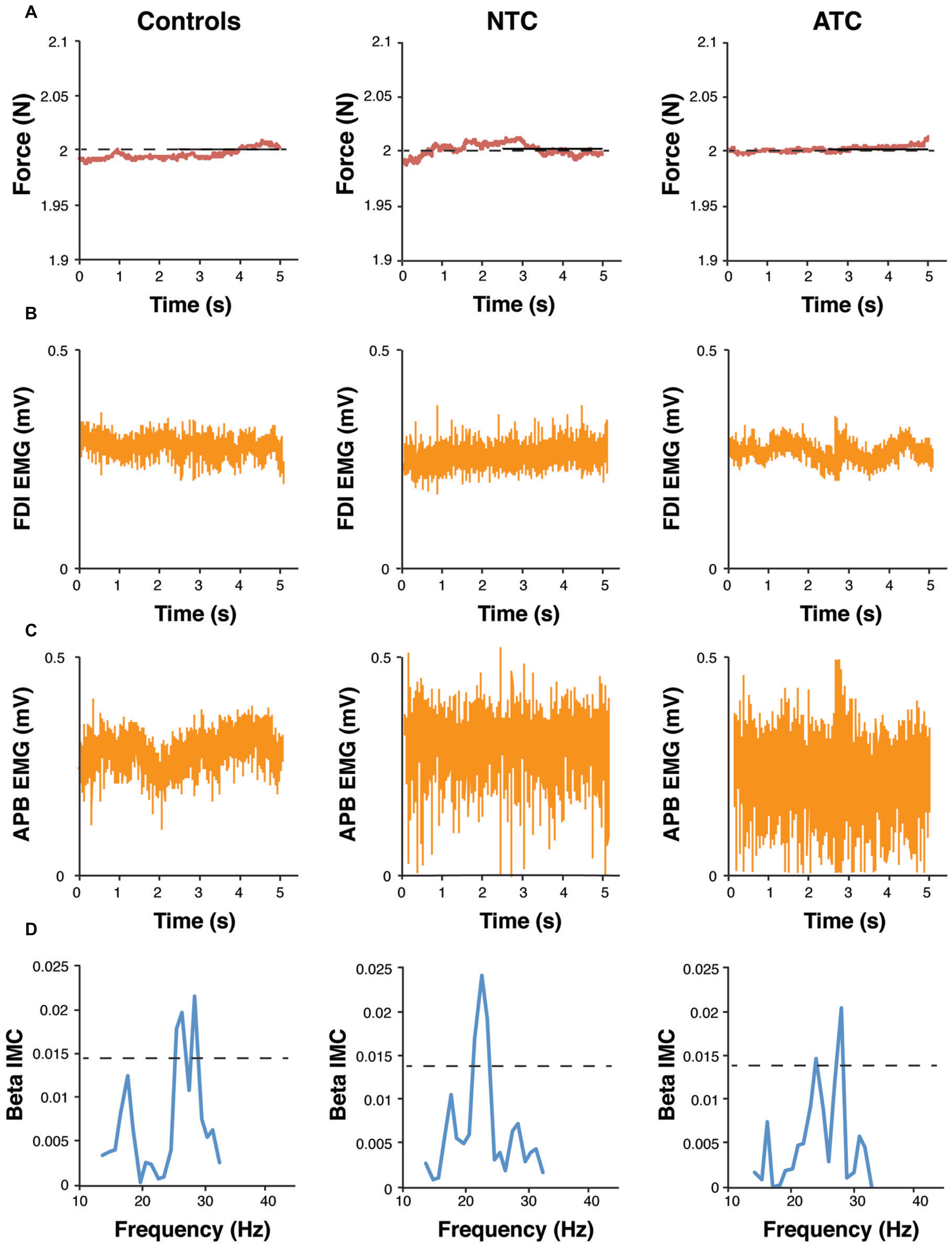

FIGURE 2 | (A) Trace of task-related force variability in a 2-Newton force, 40 s static hold task, is displayed in a sample control, novice TC, and advanced TC subject. Surface electromyography (EMG) recorded from the **(B)** *first dorsal interosseous* (FDI) and the **(C)** *abductor pollicis brevis* (AbPB) muscles of the right hand in a sample control, novice TC, and advanced TC subject. **(D)** Examples of peak beta (15–30 Hz) intermuscular coherences (IMC) in a sample control, novice TC, and advanced TC subject.

derived from (Raghunathan et al., 1996; see **Figure 4**). To summarize the statistical plan for study 1, we first carried out a 1-way test of significance for the three-group comparison using a non-parametric Kruskal–Wallis with the plan, in the case of significance, of following up with paired comparisons, using the non-parametric Mann–Whitney test to conduct the following tests: Control vs. Novice TC, Control vs. Advanced TC, and Novice TC vs. Advanced TC for a total of three planned comparisons. To account for the effect of multiple tests, significance in both the beta IMC and force variability group analyses were Bonferroni corrected with significance specified as $p = 0.0167$ (e.g., 0.05/3).

Study 2: Tactile and Proprioceptive Components of the RHI

Subjects

Fifteen TC practitioners (51.5 ± 14.1 years, 6 female) were recruited from the Brookline Tai Chi School in order to conduct the RHI task (Note: seven subjects in study 2 also participated in study 1) As in the beta IMC study, exclusion criteria for all subjects included the following: chronic arm, wrist, or hand pain in the last 2 years; any other movement or rheumatoid disorder; or recent muscle sprain to the hand, wrist, arm, or shoulder. TC practitioners must have maintained practice for at least three times per week for 12 months. All subjects gave informed consent to participate in this study in accordance with the Institutional Review Board of Brown University.

Paradigm

Subjects were seated in front of a two-compartment box that was open on the front and back such that they could place their hand inside the box. One compartment was covered by opaque black Plexiglas, and subjects were instructed to place their right hand inside this compartment such that it was hidden from view. The other compartment was transparent and positioned directly in front of the subject's chest, and a realistic looking rubber arm was placed inside of it facing the same direction as the subject's real, hidden arm, such that the rubber hand was placed eight inches laterally from the subject's midline.

During the task, subjects were told to maintain their gaze fixed on the rubber arm. The experimenter sat across from the subject and, using both index fingers, stroked digits two to four of both the subject and the rubber arm either synchronously or asynchronously at 0.5–1 Hz. This tactile stimulation lasted 2 min, and the order of synchronous and asynchronous trials was randomized. In asynchronous trials, strokes on the real arm occurred with a 180-degree offset to strokes of the rubber arm.

Following stimulation, subjects were administered a five item questionnaire derived from (Longo et al., 2008a; Jenkinson et al., 2013), which probed subjective aspects of the illusion (see **Table 1**). The experimenter read the questions aloud and prompted subjects to respond with a number from zero to six indicating their response to the question, with lower numbers indicating negative responses and greater numbers indicating positive responses. Additionally, an objective measure of susceptibility to the illusion, proprioceptive drift, was quantified by placing a ruler extending across the two-compartment box and asking participants under which number they felt their index finger rested. In order to blind the subject to any bias about his/her sense of where the hand ought to be located, the ruler was then shifted slightly such that the numbers seen by the participant were also shifted, and the subject was again asked to judge where their index finger rested beneath the ruler. This shifting and measurement was repeated one additional time, and proprioceptive drift was calculated as the mean difference between the actual location of the participant's index finger and the participant's three reported values.

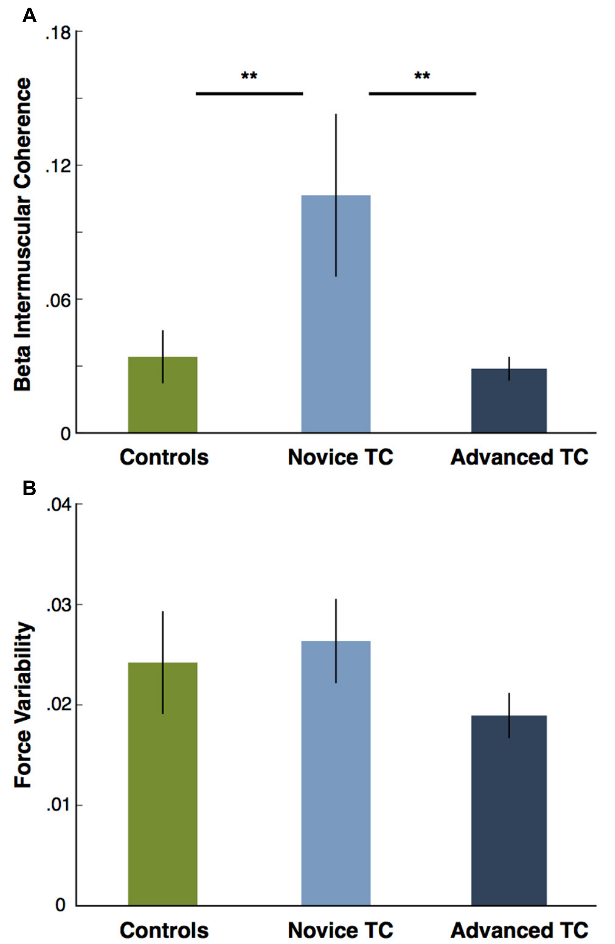

FIGURE 3 | (A) Comparison of beta IMC across three groups (controls, novice practitioners, and advanced practitioners) shows novice TC have significantly higher beta IMC than advanced practitioners (**$p < 0.005$) and controls (**$p < 0.005$) while there is no difference between controls and entire TC group or between controls and advanced TC. **(B)** Comparison of force variability across three groups (controls, novice practitioners, and advanced practitioners) shows no significant differences between groups ($p > 0.05$), although advanced practitioners manifest a trend toward a significant difference as compared with novice practitioners ($p < 0.1$). In both plots, error bars display ±1 SEM.

Analysis

To answer the question of whether TC cumulative practice was inversely associated with responses to somatosensory

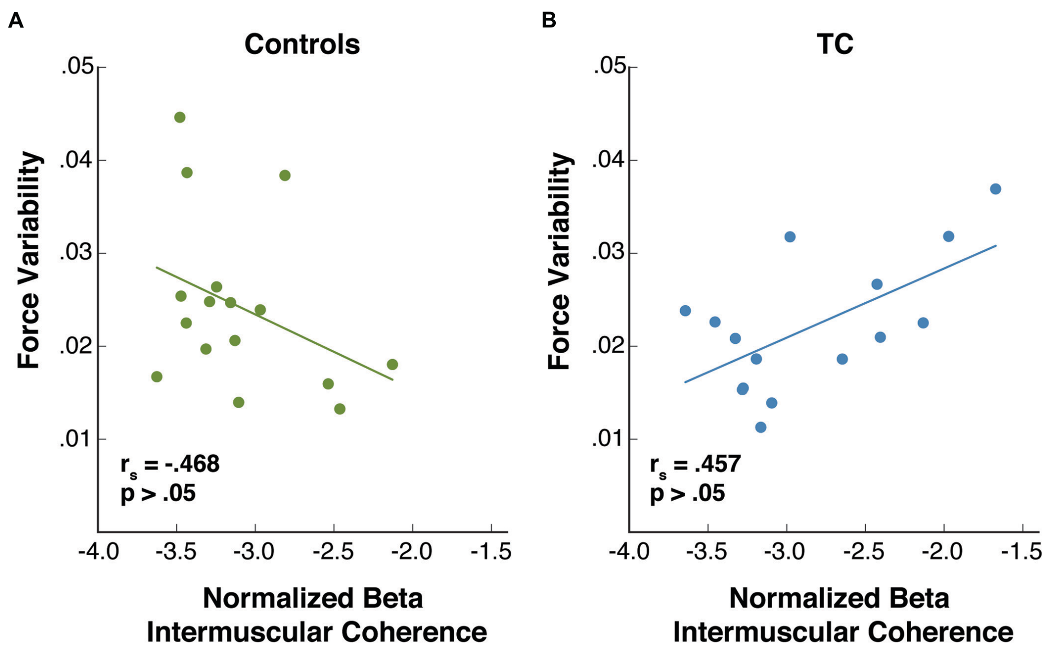

FIGURE 4 | Relationship between beta IMC and force variability in Controls and TC subjects (A) TC subjects showed no significant correlation between beta IMC and force variability (Spearman's *rho* = 0.457, *p* > 0.05) although a trend was present (*p* < 0.1). (B) Control subjects showed no significant correlation between beta IMC and force variability (Spearman's *rho* = −0.468, *p* > 0.05) although a trend was present ($p < 0.1$). The difference between the two correlation coefficients is significant ($p < 0.01$). Note: for purposes of display, data are shown here as log-transformed, while all statistical analysis was performed on non-transformed data (since tests used were non-parametric).

components of the RHI (e.g., tactile and proprioceptive responses) in addition to perceived illusory body ownership, we utilized a brief questionnaire assembled by Jenkinson et al. (2013) in an earlier study, focusing especially on responses to item #1 ("How much does it seem that the touch you are feeling is where you see the rubber hand being stroked?"), item #3 ("How much does it seem as the rubber hand is your hand?"), and item #4 ("How much does it seem as though you are losing sense of where your hand is?").

We carried out non-parametric Spearman correlations between cumulative TC practice hours and the these three questions in the questionnaire (see **Figures 5A–C**). We also carried out a non-parametric Spearman correlation between TC practice hours and an objective measure of proprioception in the RHI, proprioceptive drift (see **Figure 5D**). In study 2, since each of the two tests reflected a separate *a priori* hypothesis that focused on a separate statistical parameter, no correction for multiple comparisons was required. Therefore statistical significance was taken to be $p = 0.05$.

RESULTS

Study 1: Beta IMC

To test the hypothesis that across the three groups, increasing levels of TC experience would be associated with decreasing levels of beta IMC, we compared beta IMC in controls, novice TC, and advanced TC using the Kruskal–Wallis non-parametric one-way ANOVA, and found a significant main effect of group ($p < 0.05$; **Figure 3A**). As a follow-up, four non-parametric Mann–Whitney tests were conducted and revealed a significant difference (Bonferroni corrected to $p = 0.0167$) between novice and advanced TC ($p < 0.005$). Novice TC also showed significantly greater beta IMC than controls ($p < 0.005$), resulting in an inverted U-shaped effect of TC experience on beta IMC. As an additional comparison, using the Mann–Whitney, we also determined that there was no difference between controls and the overall TC group or between controls and advanced TC ($p > 0.05$).

To test the hypothesis that across the three groups, increasing levels of TC experience would be associated with decreasing levels of force variability, we compared force variability in controls, novice TC, and advanced TC using the Kruskal–Wallis non-parametric one-way ANOVA, and found no significant difference between groups ($p > 0.05$; **Figure 3B**). However, it is worth noting that advanced TC practitioners manifested a trend toward significantly reduced force variability when compared to novices ($p < 0.1$), but not controls ($p > 0.1$).

To characterize the relationship between beta IMC and force variability in controls vs. TC practitioners, we calculated the non-parametric Spearman correlation coefficient (**Figure 4**). No significant correlation was observed between beta IMC and force variability in TC subjects (Spearman's *rho* = 0.457, $p > 0.05$) or between beta IMC and force variability in controls (Spearman's *rho* = −0.468, $p > 0.05$). However, using an approach described in Raghunathan et al. (1996),

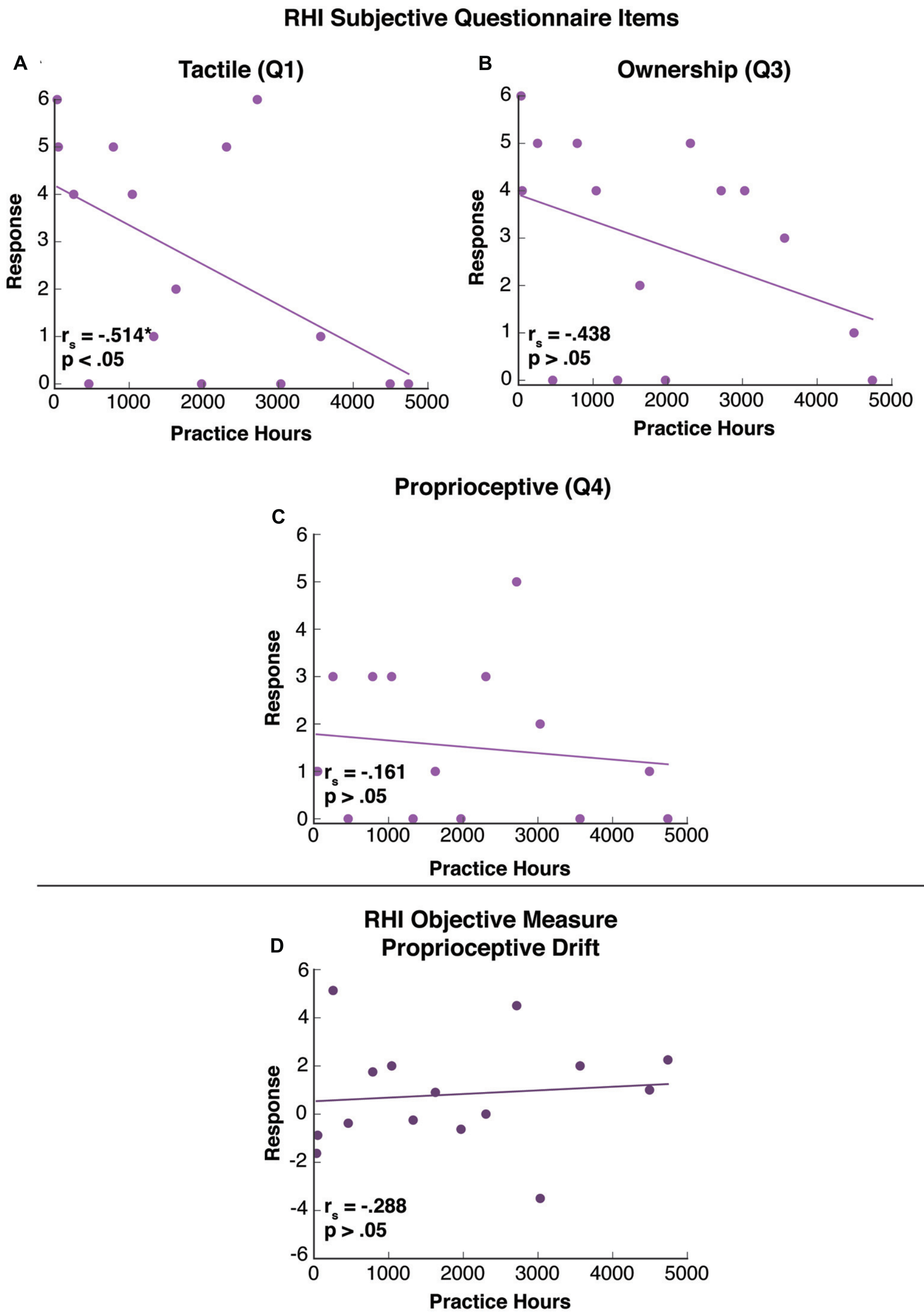

FIGURE 5 | (A) Cumulative TC practice hours are inversely correlated with subjective – tactile response to the RHI (Response to question #1: "How much does it seem that the touch you are feeling is where you see the rubber hand being stroked?" Spearman's *rho* = −0.514, $^*p < 0.05$). **(B)** Cumulative TC practice hours are not correlated with subjective – ownership responses to the RHI (Response to question #3: "How much does it seem as the rubber hand is your hand?" Spearman's *rho* = −0.438, $p > 0.05$). **(C)** Cumulative TC practice hours are not correlated with subjective – proprioceptive responses to the RHI (Response to question #4: "How much does it seem as though you are losing sense of where your own hand is?" Spearman's *rho* = −0.161, $p > 0.05$). **(D)** Relationship between cumulative TC practice hours and objective measure of proprioceptive drift in response to RHI (Spearman's *rho* = 0.288, $p > 0.05$) is non-significant.

we evaluated the statistical significance of the difference between the two correlation coefficients and found there was a significant difference between the positive correlation in TC and the negative correlation found in Controls ($p < 0.01$).

Study 2: Tactile and Proprioceptive Components of the RHI

We examined the effects of TC practice on tactile and proprioceptive elements of the RHI. In assessing the tactile components of the illusion using a non-parametric Spearman correlation, we found an inverse relationship between cumulative TC practice hours and responses to the tactile question on our administered questionnaire ("How much does it seem that the touch you are feeling is where you see the rubber hand being stroked?"; Spearman's $rho = -0.514$, $p < 0.05$; **Figure 5A**) with a median response of 2 and an interquartile range (IQR) from 0 to 5. We found no relationship between cumulative TC practice hours and responses to the question of body ownership ("How much does it seem as the rubber hand is your hand?"; Spearman's $rho = -0.438$, $p > 0.05$) (**Figure 5B**) with a median response of 4 and an IQR from 0.25 to 4.75, or to the question of proprioception ("How much does it seem as though you are losing sense of where your hand is?"; Spearman's $rho = -0.161$, $p > 0.05$; **Figure 5C**) with a median response of 1 and an IQR from 0 to 3. We also tested this correlation in an objective measure associated with proprioception, proprioceptive drift, and found there was no relationship between this metric and cumulative practice hours (Spearman's $rho = 0.288$, $p > 0.05$; **Figure 5D**).

DISCUSSION

Contrary to our initial hypothesis of a monotonic decrease in beta IMC with increasing TC experience, we found an inverted U-shaped effect of TC practice on beta IMC, in which novice practitioners presented with greater beta IMC than both controls and advanced practitioners. Furthermore, we found that TC significantly altered the relationship between beta IMC and force variability in our elderly sample, although not as expected based on studies in younger, healthy subjects (where higher beta is associated with better task performance; Witte et al., 2007; Johnson and Shinohara, 2012). In addition, TC practice elicited enhanced subjective maintenance of ongoing tactile awareness during the RHI, although we did not find a direct modulation of the subjective experience of proprioception or body ownership or an objective measure of proprioceptive drift.

The Effect of TC on Beta IMC

Our data suggest that TC affects beta IMC in a more complex manner than initially predicted. Rather than a linear decrease in beta IMC with increasing TC experience, there is an initial surge of beta IMC in novice practitioners that returns to levels equivalent to those seen in elderly controls with additional practice hours (see **Figure 3**). In this study we found that even the most inexperienced practitioners with only dozens of hours of practice showed significantly elevated beta IMC, possibly indicating that TC training elicits changes in neurophysiological function from very early in the practice. This finding suggests that neural pathways accessed by TC training may be utilized differently as practitioners' levels of expertise increase. The timeframe of the initial increase in beta IMC seen in novices is consistent with motor benefits of TC reported in 12 weeks randomized controlled trial interventions [see, for example, (Chen et al., 2012) and these benefits have been found to be maintained in studies of long term practitioners (Tsang and Hui-Chan, 2003)]. The inverted U-shaped curve has also been observed in previous studies of contemplative practice (Brefczynski-Lewis et al., 2007) and other forms of language and motor learning (Rakisona and Yermolayevaa, 2011). However, it is still unclear why these pathways, specifically beta IMC, are modulated in this way.

One possible explanation for this observed trajectory of an initial surge followed by a decrease to normal levels in beta IMC in TC practitioners, is the increasingly replicated finding that beta oscillations and beta coherence are associated with not only motor but also sensory function. Coherent activity in the beta band has been observed between muscle spindles and cortex (Baker et al., 2006) and granger causality analyses (Brovelli et al., 2004) have revealed ascending directionality in the beta band from muscles to cortex in addition to the descending cortical to muscular control. Beta power in somatosensory cortex (Jones et al., 2010) as well as in the muscles (van Ede and Maris, 2013) has also been found to predict tactile detection. These findings support the theory that beta oscillations integrate both efferent motor and afferent sensory flows of information.

Given this emerging literature, our prior hypothesis of a monotonic decrease in beta IMC may not have accounted for beta's sensory role. Taking this sensory role into account, the emphasis on somatic attention during movement in TC may shift the balance between efferent and afferent flows of sensorimotor information in beginners, while in advanced practitioners it may alter the functional significance of beta IMC to expand its ability to play a role in more efficiently filtering not only motor but also sensory information. Perhaps the initial rise in beta IMC in novice TC practitioners represents an effortful transformation in attending to afferent sensory experience, as opposed to motor experience as in controls, and with more practice this unique somatic attention becomes ingrained and more subtly and flexibly engages peripheral beta feedback loops. In other words, sensorimotor attention in TC may train efferent-afferent feedback loops and enhance the ability of beta oscillations to filter sensory and motor information, similar to the way mindfulness enhances the ability of alpha oscillations to filter somatosensory information in cortex (Kerr et al., 2013).

Partial support for this theory lies in the opposing correlations observed between beta IMC and force variability in our TC practitioners and controls. Although non-significant, in TC practitioners there was a trend toward lower force variability (i.e., better performance) being associated with *lower beta IMC*, while in controls the opposite relationship was observed, with a trend toward better task performance and lower force variability being associated with *higher beta IMC* (see **Figure 4**). One possible explanation for this contrast could be due to the specific manner in which TC utilizes beta IMC. In this context of TC practice, perhaps lower levels of beta IMC permit more reliable transmission of tactile and proprioceptive information, allowing advanced TC practitioners to engage with their sensory experience with heightened awareness of somatic sensation.

More rigorous studies utilizing electroencephalography (EEG), granger causality, and integrated sensory and motor tasks must be conducted to fully examine these hypotheses, but nonetheless the data presented here provide preliminary evidence for a complex effect of TC practice on neurophysiological indices underlying sensorimotor function, such as beta IMC. Additionally, the data suggests that future studies should investigate the clinical role of TC training in Parkinson's patients, a motor disorder characterized by maladaptive beta oscillations (Jenkinson and Brown, 2011).

The Effect of TC on the RHI

As hypothesized, we found that with greater experience, TC practitioners were less likely to misattribute the location of the tactile stimulation on their real, hidden hand to the visible, rubber hand (**Figure 5A**). This result suggests that TC practice is associated with subjective reports of enhanced ongoing awareness of one's own tactile afferent processes, and is also consistent with previous findings of enhanced tactile acuity in TC (Kerr et al., 2008). However, we did not find a similar effect in an objective measure of proprioception, proprioceptive drift (**Figure 5D**). We also observed null findings in additional subjective measures, e.g., body ownership (**Figure 5B**) and proprioception (**Figure 5C**).

Taken together, these findings suggest that certain practices, such as TC observed here, may train distinct components of the RHI. Previous findings have already demonstrated that these components that are often considered together actually make up distinct responses that are not always directly correlated (e.g., proprioceptive drift and sense of ownership experience (Rohde et al., 2011; Abdulkarim and Ehrsson, 2015). In this study we found that TC practice exerted specific effects on tactile and not proprioceptive subjective experience in the RHI. One possible interpretation of these findings is that there may exist a tradeoff between an improved sense of proprioception and enhanced plasticity, and given prior evidence that TC practice induced plastic changes in specifically tactile acuity (Kerr et al., 2008), our sample of TC practitioners may lack proprioceptive benefits. Additionally, as predicted by Bayesian causal inference models (Kilteni et al., 2015; Samad et al., 2015) this increased tactile awareness (or reduced perceptual error) in our sample of TC practitioners may affect the overall sense of illusory body ownership. However, more rigorous examination of the individual factors thought to underlie the RHI must be conducted in TC practitioners in order to support these claims.

The present study's results suggest TC may alter the RHI in highly specific and subtle ways that an undifferentiated approach to the RHI may miss. The specificity of this data may also explain the negative finding seen in a prior study of RHI and yoga (David et al., 2014), which did not consider the different components of the illusion separately but instead evaluated yoga's effect on a compounded, scored measure. Additional future directions should include studies correlating basic sensorimotor beta rhythm network coherence and higher-order RHI in order to more fully understand the possible relation between these two variables. Early reports suggest beta rhythm transmission from motor areas may enable the multisensory perceptual processes that underlie the RHI [see for example (Mancini et al., 2013)].

Despite their exploratory nature, these data may provide some clues about how to model sensorimotor mechanisms underlying TC's efficacy in enhancing sensorimotor function, especially in the elderly. Specifically, these data suggest that, given the strong difference we found between novices and advanced TC beta IMC, there may be developmental phases over the course of TC practice such that novices may be using very different sensorimotor neural processes than those who have undertaken more than 1000 h of practice. More data collected on the behavioral changes and experiential self-reports of practitioners across the developmental span of expertise would be very helpful. Moreover, what the RHI data suggest is that there may be definitive shifts across this developmental span in which practitioners undergo changes in "embodiment" e.g., enhanced sensory and motor processing elicited by increased somatic attention during practice. In other words, practitioners' experiences of somatic attention and sensory and motor performances may shift over time; the current study's focus on the significant effects of practice over time may shed light on TC as a modality for retraining basic sensorimotor neural substrates (e.g., beta rhythm network coherence) and higher-order multisensory body representation (e.g., specific aspects of the RHI).

Considered from a more theoretical perspective, the correlation of TC practice with the self-reported maintenance of tactile awareness during the RHI provides partial support for an intriguing hypothesis derived from some sources in the TC instructional literature (Wayne and Fuerst, 2013). The hypothesis states that over time, cumulative TC practice may mechanistically move practitioners toward a more unified, less fragmented and more "spacious" sense of their own internal bodily experience, which is sometimes described by practitioners' use of highly qualitative words such as "presence" or a sense of energy in the body, sometimes referred to by the Chinese term "qi" (Yang, 2005). The broader implications of these ideas are beyond the scope of this exploratory study. However, further investigation of the experience of TC practitioners, utilizing qualitative tools recently used in studies of the phenomenology of the RHI (Valenzuela Moguillansky et al., 2013) could be a productive and important avenue for future research.

Limitations

This study has several important limitations, some of which are quite prominent.

First, in study 1, the data are cross-sectional so self-selection confounds and spurious causative agents cannot be ruled out and although there is an age-matched control group, the study does not use the highest type of control condition which would also control for practice-related activity (e.g., would compare TC to some other type of activity-focused group such as "tango dancers" in order to rule out the effects of group-related physical and mental practice activity). In addition, it is important to note that the samples sizes are also too small in our study of beta IMC and force variability ($n = 31$) and the RHI ($n = 15$) to draw definitive conclusions and should be replicated in larger samples.

Second, an important limitation in our study of beta IMC is that beta IMC is not identical to beta CMC, although the two measures are highly related (Kilner et al., 1999; van Ede and Maris, 2013). In order to adequately investigate the involvement of cortex in the hypothesized body awareness mechanism a more rigorous methodology using EEG-EMG and directed coherence analyses between primary somatosensory cortex, primary motor cortex, and the muscles must be conducted.

Third, a key limitation in our investigation of the RHI is that we did not compare TC with a control group so we cannot say whether TC practice is associated with decreased subjective tactile responses to the RHI when comparing TC practitioners to normal controls.

CONCLUSION

We found that TC practice modulates beta IMC in an inverted U – shaped trajectory, where novice TC practitioners manifest a sharp increase in beta IMC as compared with controls that with increasing practice again returns to levels equivalent to controls as practitioners become more advanced. This finding suggests that TC practice elicits complex changes in sensory and motor processes over the developmental lifespan of TC training. Additionally, the inverse association between beta IMC and force variability typically observed in healthy, younger populations actually showed a trend in the opposite direction in our TC population, such that higher levels of beta IMC actually indicated higher force variability (i.e., worse task performance) in this group. Finally, we found that with increasing experience, TC practitioners were less likely to misattribute a touch on their hand during the RHI to the fake rubber hand. At the same time, however, we found no significant relationship between cumulative TC experience and proprioceptive drift or sense of body ownership.

While the results of this investigation must be approached with caution, given that the two experiments used cross-sectional design, small sample sizes, and based all analysis on EMG measures, this study provides preliminary validation for a theoretical model in which TC practice enhances filtering of sensorimotor information through peripheral feedback beta rhythm efferent-afferent loops and alters awareness of tactile sensations during the RHI. This work is the first to examine TC practice at not only the level of sensorimotor information processing but also the level of integrated body awareness. The findings presented here may help to shed light on the mechanisms underlying the widespread benefits observed with TC in symptoms associated with aging and difficult illnesses such as Parkinson's disease.

AUTHOR CONTRIBUTIONS

All authors listed designed and performed research, and CK and UA analyzed data and wrote the paper.

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Changes in neural resting state activity in primary and higher-order motor areas induced by a short sensorimotor intervention based on the Feldenkrais method

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We use functional magnetic resonance imaging to investigate short-term neural effects of a brief sensorimotor intervention adapted from the Feldenkrais method, a movement-based learning method. Twenty-one participants (10 men, 19–30 years) took part in the study. Participants were in a supine position in the scanner with extended legs while an experienced Feldenkrais practitioner used a planar board to touch and apply minimal force to different parts of the sole and toes of their left foot under two experimental conditions. In the *local* condition, the practitioner explored movement within foot and ankle. In the *global* condition, the practitioner focused on the connection and support from the foot to the rest of the body. Before *(baseline)* and after each intervention *(post-local, post-global)*, we measured brain activity during intermittent pushing/releasing with the left leg and during resting state. Independent localizer tasks were used to identify regions of interest (ROI). Brain activity during left-foot pushing did not significantly differ between conditions in sensorimotor areas. Resting state activity (regional homogeneity, ReHo) increased from *baseline* to *post-local* in medial right motor cortex, and from *baseline* to *post-global* in the left supplementary/cingulate motor area. Contrasting *post-global* to *post-local* showed higher ReHo in right lateral motor cortex. ROI analyses showed significant increases in ReHo in pushing-related areas from *baseline* to both *post-local* and *post-global*, and this increase tended to be more pronounced *post-local*. The results of this exploratory study show that a short, non-intrusive sensorimotor intervention can have short-term effects on spontaneous cortical activity in functionally related brain regions. Increased resting state activity in higher-order motor areas supports the hypothesis that the *global* intervention engages action-related neural processes.

Keywords: sensorimotor learning, functional magnetic resonance, resting state activity, Feldenkrais method, touch, foot

Introduction

The Feldenkrais method is a movement-based learning method aimed at improving organization of the body in action (Feldenkrais, 1947; Buchanan, 2012). One basic assumption of this approach is that movement variation, guided somatosensory attention, and hands-on manipulation can provide meaningful information to the nervous system by clarifying functional relationships along the body and with the environment (e.g., connection between body parts, support from the floor, movement distribution, orientation in space). In this explorative study, we investigate the role of the practitioner's focus on functional relationships between body parts in one particular Feldenkrais technique applied to the foot, the "artificial floor" (e.g., Feldenkrais, 1981), by assessing the neural effects of two subtly different forms of the manipulation. In the *local* condition, the manipulation is focused on anatomical relationships and mobility within the foot. In the *global* condition, the manipulation explores the connections from the foot to the rest of the body, focusing on the function of the foot for body support. We use functional magnetic resonance imaging (fMRI) to investigate potential short-term effects of these two forms of the artificial floor on neural activity during a functionally related motor task (gently pushing with one foot onto a horizontal support surface) as well as during resting state. We hypothesized that the *local* manipulation would lead to increased activity in primary sensorimotor areas representing the stimulated foot, while the *global* manipulation would engage more widespread and higher-level motor areas.

The Feldenkrais Method

The Feldenkrais method consists of a system of ideas and principles concerning efficient and effective movement organization. It was developed by Moshe Feldenkrais in the second half of the 20th century (Feldenkrais, 1947, 1981), partly based on his extensive experience with the martial art of Judo (Feldenkrais, 1952). These principles are applied in movement lessons, which can be either taught verbally to a group of people or taught individually by guidance through manual touch. The Feldenkrais method is used by people of varying motor abilities and in a variety of settings, ranging from performing arts (Nelson, 1989; Schlinger, 2006) to rehabilitation (Ives and Shelley, 1998; Buchanan, 2012).

Most bodily actions require the coordination of multiple components of the sensorimotor system to realize specific action goals (e.g., reaching a target with the hand) while maintaining other systemic functions (e.g., balance, breathing). One assumption of the Feldenkrais method is that general improvement in movement organization can be achieved by clarifying the functional relation between components that need to be integrated in action. This can be approached, for instance, by exploring the coordination between different body parts, by systematically varying postural and balance constraints, by guiding somatosensory attention to different aspects of a movement (through verbal instruction or manual touch), or by mental imagery. Feldenkrais lessons often begin with small-amplitude and slow movements in order to enhance processing of sensory information and facilitate exploration of alternatives to habitual movement and perception patterns. This is in line with Nikolai Bernstein's theoretical work on motor learning: "Certainly, the most sensible and correct training would be organized in a way that combined a minimization of effort with a large variety of well-designed sensations and that created optimal conditions for meaningfully absorbing and memorizing all these sensations" (Bernstein, 1996, p. 181). It has been argued that the approach is consistent with general principles of sensorimotor learning (Connors et al., 2010). However, scientific evidence for the potential effectiveness of the Feldenkrais method remains limited (Ives and Shelley, 1998; Buchanan, 2012).

Active movement and perception play an important role for sensorimotor development, learning, and rehabilitation (Held and Hein, 1963; Krebs et al., 2003; Lotze et al., 2003; Berthouze and Goldfield, 2008; Iftime-Nielsen et al., 2012; Adolph and Robinson, 2015). The active role of the participant is evident in Feldenkrais group lessons, which are performed by the participant under verbal guidance, but less obvious in manual interventions, where it is the practitioner who initiates movements and manipulates the participant's body parts. Feldenkrais proposed that the students' nervous system becomes more actively involved in the interaction, relating the manipulation to self-generated action, if the practitioner attends to minute responses of the student, exploring which variations of a movement (e.g., in direction and orientation) connect most clearly to other body parts and create a harmonious movement among them. This idea is applied in the "artificial floor" manipulation investigated in the present study.

The "Artificial Floor"

During the artificial floor manipulation (Feldenkrais, 1981, pp. 140–142), the participant is lying on the back, with the legs comfortably supported by rollers, while the practitioner touches one foot by means of a planar board (**Figure 1**, video in Supplementary Material). With the participant's legs positioned on the rollers, a small pressure applied to the toes or different parts of the sole of the foot, can create a *local* movement within the foot (the toes, the metatarsals, the ankle), but the manipulation can also have a more *global influence,* reaching other body parts via legs and spine, such as the pelvis, trunk, head and shoulders. Whether and how movement is transferred to different body parts, depends on the stimulation (contact point, direction, amplitude) and the neuromuscular state of the body (e.g., activation of muscles). Importantly, the goal of the practitioner is not to induce substantial movement in the foot or along the body, but to provide the participant's nervous system with sensory information about the *connection* from the foot to the rest of the body and, ultimately, with a sensation of the foot's function for body support under various orientations and contact points of the support surface. To achieve this, the practitioner adjusts the direction, timing and applied force to the configuration of the participant's foot and other body parts, as well as to the participant's responses to the stimulation.

Application of the artificial floor in a complete Feldenkrais lesson usually proceeds from a more *local* exploration of the mobility and anatomical relationships within the participant's

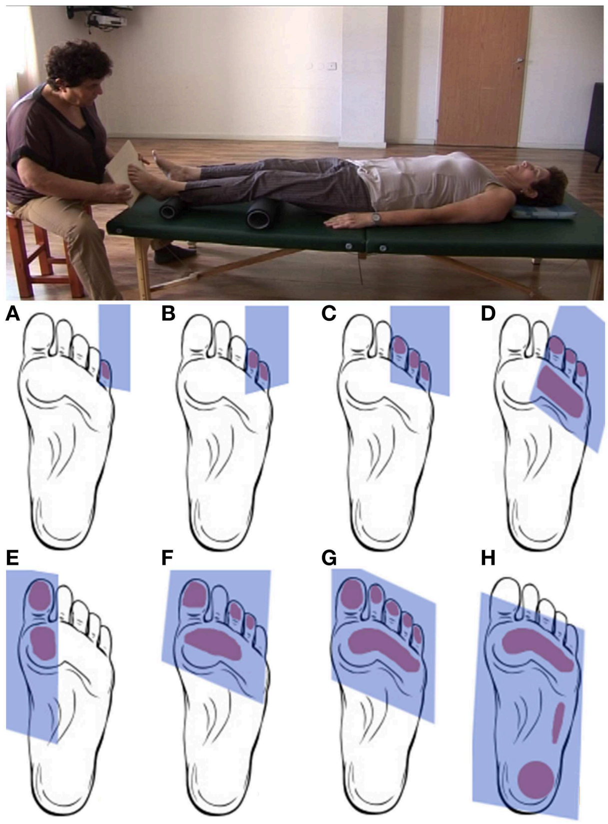

FIGURE 1 | Upper panel. Positions of practitioner and participant during the artificial floor manipulation. *Lower panel*. Typical contact areas between board and foot during the artificial floor manipulation. The manipulation will typically proceed from touching and gently pushing individual or multiple toes **(A–C)** to gradually include larger parts of the foot sole **(D–G)** up to the entire foot **(H)**. Rather than being a simple tactile stimulation, the manipulation is individualized and interactive in the sense that the practitioner attends and adjusts to the response of the foot, potentially resulting movement in other body parts, as well as any other observable responses from the participant, for instance during the "return movement" when the contact is released. The present study compares two forms of the manipulation. In the *local* condition, the artificial floor is applied with the intention to explore mostly the mobility within the foot. The *global* intervention has a similar procedure, but the focus of the manipulation is on the connection and support from the foot to higher body parts. Exemplary videos of the Artificial Floor intervention can be found in the Supplementary Materials.

foot to a more *global* mode, in which the practitioner explores the connection from the foot to the rest of the body, focusing on the function of the foot for body support. Presumably, differences in the attentional focus and intention of the practitioner lead to subtle differences in contact points as well as force directions and amplitudes during the intervention. These physical differences are not the subject of the present study and may indeed be difficult to define quantitatively across participants, as they are not pre-determined but develop individually and interactively during the manipulation, as described above. However, we hypothesized that the two forms of the manipulation induce distinct effects at the neural level which may be relatively invariant across participants due to the practitioner's invariant intentional focus (*local* vs. *global*) guiding the interactive manipulation. It should be noted that both forms of the artificial floor are typically used in Feldenkrais lessons, not as separate interventions but in combination. The distinction between the *local* and *global* manipulation is made in the present study in order to elucidate the role of the practitioner's attention to functional relationships between body parts.

Neuroscientific Background

The artificial floor manipulation reverses the usual relation between body and support surface: it is not the feet that "look for support" from the floor, but a "support surface"—a planar board moved by the practitioner's hands—that approaches and makes physical contact with the feet. Feldenkrais assumed that this allows the participant to experience the use of the foot for body support under various conditions of contact area and orientation, thereby eliciting a learning process that may influence subsequent use of the foot in standing and walking. Two major, non-trivial assumptions are that this is possible even though the participant is lying supine, without need for active postural stabilization, and despite the fact that the forces applied to the foot during the manipulation are much smaller than forces during bipedal standing or walking.

Tactile perception and proprioception from foot and ankle play a crucial role in stabilization of upright posture (Kavounoudias et al., 1998, 2001; Maurer et al., 2006; Wright et al., 2012), but it is a priori not evident to what extent sensory information provided in a lying position—such as during the artificial floor manipulation—will be interpreted by the nervous system in terms of balance control. It has been shown that neural activity in cortical and sub-cortical brain regions during proprioceptive ankle stimulation in a supine lying position in the magnetic resonance (MR) scanner correlates with balance performance (Goble et al., 2011). Moreover, mental imagery of standing or walking while lying in an MR scanner has been found to activate functionally plausible brain regions, including premotor and supplementary motor areas, basal ganglia and the cerebellum (Malouin et al., 2003; Jahn et al., 2004). These findings suggest that the nervous system can relate to balance and gait even in the physically constrained conditions determined by the MR scanner, in particular, this appears to be possible in a supine position.

Primary sensorimotor cortices are somatotopically organized along the central sulcus, with upper extremities and trunk represented more laterally and lower extremities represented in the medial wall (Penfield and Boldrey, 1937; Lotze et al., 2000; Zeharia et al., 2012). Brain activity in sensorimotor areas has been found to be less lateralized for the lower compared to the upper limbs (Kapreli et al., 2007). Relatively isolated foot movements (at the ankle joint) induce activity in medial sensorimotor cortex as well as higher-order motor areas, such as the supplementary motor area (SMA), premotor cortex and cingulate motor areas (CMA) (Dobkin et al., 2004). Comparing active to passive as well as electrically stimulated ankle movement, Francis et al. (2009) found increased activity in SMA, premotor cortex, dorsolateral prefrontal cortex as well as CMA for self-generated compared to externally generated movements. SMA and CMA were also found to be activated during preparation of active ankle movements compared to anticipation of passive movement (Sahyoun et al., 2004). These results indicate that, similar to upper-limb movements, primary sensorimotor cortices are activated even during externally-generated foot movements, while activity in higher-order motor areas (e.g., SMA and CMA) is related to preparation and performance of self-generated action.

Close links between action and perception have been postulated early in the history of experimental psychology (Lotze, 1852; James, 1890) and are corroborated by more recent behavioral and neuroimaging studies establishing bi-directional associations between movements and their sensory consequences (Greenwald, 1970; Prinz, 1990; Hommel et al., 2001; Kühn et al., 2010). Thus, neural action representations can be activated in the nervous system by a sensory stimulation that shares features with the sensory consequences of that action. To our knowledge, this has mostly been investigated using visual or auditory sensory stimuli (Brass et al., 2000; Paulus et al., 2012; Verrel et al., 2014). The physical stimulation of the foot in the artificial floor intervention is very different from the stimulation during actual standing, both in terms of amount of force and contact area. However, the *global* manipulation (if successful) shares an essential feature with the use of the foot for body support, as it aims to generate sensory information emphasizing the connection from the foot to other body parts. As a consequence of bi-directional action-perception links, we expected the *global* manipulation to elicit a corresponding neural action pattern (of using the foot to support the body) in the participant's nervous system.

Resting state fMRI offers the possibility to study spontaneous brain activity in the absence of an instructed task. It may therefore be especially appropriate to investigate potential changes in neural dynamics induced by behavioral or neural interventions (Guerra-Carrillo et al., 2014). For instance, short-term effects of a tactile (comparing "real" to sham acupuncture) intervention have been demonstrated on functional connectivity during resting state (Dhond et al., 2008). Also, extensive practice of new sensorimotor tasks influences spontaneous brain activity in functionally specific ways (Albert et al., 2009; Taubert et al., 2011; Vahdat et al., 2011). Finally, resting state activity has also been shown to be related to subjective experience (in this case, amount of unwanted thought) during the measurement (Kühn et al., 2013). Resting state analysis is therefore promising to study neural correlates of potential short-term effects of the artificial floor intervention.

The Present Study

Anecdotal evidence suggests that the artificial floor intervention described above can have short-term effects on participant's use and subjective experience of the feet and rest of the body, such as a clearer contact to the floor and support/push from the foot to the head during standing and walking directly after the intervention. As the intervention itself can hardly induce any peripheral changes (e.g., in muscle-tendon length, muscle force), such effects would have to be due to changes in sensorimotor organization at the level of the central nervous system. The aim of the present exploratory study is to investigate these hypothesized neural changes in terms of brain activity in a functionally related foot-pushing-task as well as during resting state. In addition, we hypothesized that a subtle variation in the application of the artificial floor affects the way in which the manipulation engages the participant's nervous system and thereby influence subsequent neural activity during related motor tasks or during resting state. More specifically, we predicted that the *local* intervention, exploring the movement *within* the foot in response to touch at the toes and different parts of the foot sole, would mainly increase processing in brain areas representing that specific body part. In contrast, applying the artificial floor with a *global* focus on the motor function of body support, was hypothesized to engage broader and/or higher-level neural action representations.

To assess potential changes in neural organization following the two forms of the artificial floor manipulation (*local, global*) described above, we use fMRI to measure brain activity during a motor task mimicking the use of the foot for body support in a supine position (gently pushing with the foot onto a horizontal support surface) as well as resting state activity before and after each intervention (with the feet standing on the same support surface). The intervention was carried out by an expert Feldenkrais practitioner with more than 30 years of professional experience (one of the authors, EA). In order to minimize perturbation due to repositioning, the intervention and all tasks were carried out while participants were lying in the MR scanner. An independent localizer task before the experiment was used to determine regions of interest (ROIs) activated during the foot-pushing task. Based on the above reasoning, we predicted that application of the *local* artificial floor would lead to an increased activity in regions (both during pushing and resting state) in sensorimotor areas representing the stimulated foot. For the *global* artificial floor intervention, we predicted more widespread activity including higher-level motor areas, reflecting a more function/action-related neural processing.

Methods

Participants

Twenty-one participants (10 men, age range 19–30 years, mean age 24.8 years) took part in the study after written informed consent and approval of the Ethics committee of the German Psychological Society (DGPs). According to self-report, all participants were right-handed and did not have any history of neurological disorder, chronic pain, or medical conditions impairing movement or balance. Participants were also selected to have previously participated in MR studies, in order to minimize the likelihood of physical or emotional discomfort during the experiment. Prior to the study, participants were informed that the goal of the study was to investigate the link between perception and movement in tasks involving being touched at the foot sole and gently pushing the foot against the floor, respectively. No reference was made to the Feldenkrais method.

Experimental Protocol

A highly experienced and internationally recognized practitioner and teacher of the Feldenkrais method (one of the authors,

TABLE 1 | Overview of the experimental protocol in the MR scanner.

Condition	Leg position	Tasks	Duration (min)
Functional localizer	Both feet standing	Push left, push right, rest	6
Left push *(baseline)*	Left foot standing, right leg long	Push left, rest	4
Resting state *(baseline)*	Both feet standing	Rest	3
Intervention *(local/global)*	Both legs long	Rest	3
Left push *(post-local/post-global)*	Left foot standing, right leg long	Push left, rest	4
Resting state *(post-local/post-lobal)*	Both feet standing	Rest	3
Intervention *(global/local)*	Both legs long	Rest	3
Left push *(post-global/post-local)*	Left foot standing, right leg long	Push left, Rest	4
Resting state *(post-global/post-local)*	Both feet standing	Rest	3

EA) instructed participants for the active movement tasks, repositioned participants' legs between conditions, and carried out the intervention ("artificial floor") in the scanner. **Table 1** gives an overview of the experimental protocol. For the *functional localizer task* (6 min), performed at the beginning of the experiment, participants had both knees bent, the feet standing on a solid, horizontal support surface, positioned at the same vertical level as their body. Participants were (previously) instructed to repeatedly push the foot into the support surface and release again, performing this movement gently and with as little effort as possible while sensing any resulting somatosensory sensations along their body. The pushing movement was performed in 20-s blocks, randomized for the left and right foot, with 20-s resting periods between active blocks. Eyes were open during this task. The tasks were cued by visual stimuli, with a black screen denoting rest period and a green screen with centrally presented letter L (R) denoting pushing with the left (right) foot.

Subsequently, participants performed a push/release task (4 min, alternating 20-s blocks of push/release and rest) with only their left foot standing on the support surface (the right leg was long, supported by cushions and rollers for the participant's comfort). Participants were instructed to keep their eyes closed during this task in order to enhance somatosensory attention to the body (Marx et al., 2003). This task was organized in alternating 20-s blocks of activity and rest, cued by a white and black screen, respectively. The strong brightness contrast allowed the cues to be perceived even with closed eyes. This push/release task was followed by a *baseline resting-state* period (3 min), during which participants had both knees bent, with the feet standing on the support surface, and with the instruction to close their eyes and rest.

During the artificial floor intervention (see **Figures 1**, **2**, video in Supplementary Material), the participants' legs were both lying on rollers while the Feldenkrais practitioner gently touched the participant's bare left foot by means of a planar board (3 min). The participant's sock was removed from the left foot prior to each part of the intervention, in order to allow differentiated touch of the foot, and put back on directly afterwards to avoid cooling. During the *local* manipulation, the intention of the practitioner delivering the stimuli was to explore movement *within* the left foot, that is, touching and applying minimal force to toes, balls, or the whole sole of the foot, investigating the resulting movement in the toes, foot and ankle. During the *global* manipulation, the experimenter delivered comparable tactile stimuli through the board, but now exploring the connection from the foot to the rest of the body and emphasizing the role of the foot for body support. Each of the two forms of the intervention *(local, global)* was followed by the pushing task with the left foot (4 min) and the resting state task (3 min) described above. The order of intervention conditions (*local, global)* was counterbalanced across participants. The Feldenkrais practitioner was only informed about the order of the conditions (*local, global*) before the first intervention with each participant, such that her initial interaction with the participant was not influenced by this information.

FIGURE 2 | Experimental setup, with the practitioner (EA) performing the artificial floor intervention in the MR scanner.

The net scanning time was approximately 45 min. After the experiment, participants were informally interviewed about potential changes they experienced in the pushing movement after the intervention, during upright standing after the experiment (e.g., weight distribution and contact of the feet to the floor), any discomfort during the experiment, and any potential previous experience with the Feldenkrais method.

Scanning Procedure

Images were collected on a 3T Magnetom Trio MRI scanner system (Siemens Medical Systems, Erlangen, Germany) using a 32-channel radiofrequency head coil. The structural images were obtained using a three-dimensional T1-weighted magnetisation prepared gradient-echo sequence (MPRAGE) based on the ADNI protocol (www.adni-info.org) [repetition time (TR) = 2500 ms; echo time (TE) = 4.77 ms; $TI = 1100$ ms, acquisition matrix = 256 × 256 × 176, flip angle = 7°; 1 × 1 × 1 mm^3 voxel size]. Functional images, both for the functional localizers and resting state analysis, were collected using a T2*-weighted echo planar imaging (EPI) sequence sensitive to blood oxygen level dependent (BOLD) contrast ($TR = 2000$ ms, $TE = 30$ ms, image matrix = 64 × 64, FOV = 216 mm, flip angle = 80°, voxel size 3 × 3 × 3 mm^3, 36 axial slices).

fMRI Data Pre-Processing

The fMRI data were analyzed using SPM8 software (Wellcome Department of Cognitive Neurology, London, UK). For the functional analysis (pushing task), the first four volumes of all EPI series were excluded from the analysis to allow the magnetisation to approach a dynamic equilibrium. Data processing started with slice time correction and realignment of the EPI datasets. A mean image for all EPI volumes was created, to which individual volumes were spatially realigned by means of rigid body transformations. The structural image was co-registered with the mean image of the EPI series. Then the structural image was normalized to the Montreal Neurological Institute (MNI) template (resampling voxel size of 3 × 3 × 3 mm), and the normalization parameters were applied to the EPI images to ensure an anatomically informed normalization. Participants showing head motion above 3.5 mm of maximal translation (in any direction of x, y, or z) and 2.0° of maximal rotation during scanning would have been excluded (this was not the case for any participant). A spatial filter of 8 mm full-width at half maximum (FWHM) was used. Low-frequency drifts in the time domain were removed by modeling the time series for each voxel by a set of discrete cosine functions to which a cut-off of 128 s was applied.

For the resting state analysis, the first five volumes were discarded to allow the magnetisation to approach a dynamic equilibrium, and for the subjects to get used to the scanner noise. Part of the data pre-processing, including slice timing, head motion correction (a least squares approach and a 6-parameter spatial transformation) and spatial normalization to the MNI template, were conducted using the Data Processing Assistant for Resting State fMRI toolbox (DPARSF; Chao-Gan and Yu-Feng, 2010). A spatial filter of 4 mm FWHM was used. After pre-processing, linear trends were removed and the fMRI data were temporally band-pass filtered (0.01–0.08 Hz) to reduce low-frequency drift and high-frequency respiratory and cardiac noise (Biswal et al., 1995).

fMRI Data Analysis

Brain activity during the pushing tasks was analyzed at the first (within-subject) level using regressors for *left* and *right* pushing blocks. Each block (20 s duration) was convolved with a hemodynamic response function and head movement parameters were included in the design matrix. We were interested in the contrast comparing left and right pushing (functional localizer) as well as left pushing compared to rest (functional localizer and pushing task during the experiment). Resting state activity was analyzed in terms of regional homogeneity. Based on the fact that fMRI activity is typically spatially clustered (Tononi et al., 1998), this analysis approach determines voxels at which BOLD fluctuates in synchrony with its neighboring voxels (Zang et al., 2004; Wu et al., 2007). The analysis was performed with the toolbox DPARSF (Chao-Gan and Yu-Feng, 2010), using Kendall's coefficient of concordance of the time series of a given voxel with those of its nearest 26 neighbors. ReHo was calculated within a brain-mask, which was obtained by removing the tissues outside the brain using the software MRIcron (https://www.nitrc.org/projects/mricron).

The resulting images were entered into a series of one-sample T-tests at the second (between-subject) level. For the functional localizer task, the resulting SPMs (*left-push* > *right-push*, *left-push* > *rest*) were thresholded at $p < 0.05$ with familiy-wise error correction (FWE). For the pairwise comparisons of resting state activity (ReHo) and functional activations in the pushing task before and after the intervention, the resulting statistical maps (*post-local* > *baseline*, *post-global* > *baseline*, *post-local* > *post-global*, *post-global* > *post-local*) were thresholded at $p < 0.005$ (uncorrected) with an additional cluster size threshold of $k = 42$. The required cluster size was determined by Monte Carlo simulation (AlphaSim; Ward, 2002) to ensure that the probability of type I error was not greater than 0.05. Reported coordinates correspond to the MNI coordinate system.

Regions of interest (ROIs) were defined based on brain activation during the functional localizer task at the beginning (*left-push* > *right-push*, *left-push* > *rest*). Mean ReHo values in the three conditions (*baseline, post-local, post-global*) in these ROIs were extracted using MarsBaR toolbox (Brett et al., 2002) and compared using paired T-tests.

Results

Significant brain activity during pushing (during localizer or during experiment) and differences in ReHo between conditions are shown in **Figures 3**, **4**, and reported in more detail below. Detailed results are only reported for primary and higher-order sensorimotor brain regions. Thresholded SPMs for all contrasts resulting in statistically significant effects are available as Supplementary Material for further inspection.

Functional Activity during Pushing

Push-related activity in the functional localizer prior to the experiment was analyzed in two ways. Comparing *left-push* to *rest* (**Figure 3A**), we found a large significant cluster in medial sensorimotor cortex with peak activation in right medial motor cortex ($p < 0.05$, FWE; 15, −34, 64; 543 voxels; $Z = 6.37$) as well as more lateral clusters (see Supplementary Material). Comparing *left-push* to *right-push* (**Figure 3B**) revealed a significant cluster in right medial motor cortex ($p < 0.05$, FWE; 16 voxels; 9, −25, 64; $Z = 5.05$).

Aggregating pushing-related activations (*left-push* > *rest*; **Figure 3C**) across the three time points of the experiment *(baseline, post-local, post-global)* shows similar activation to the

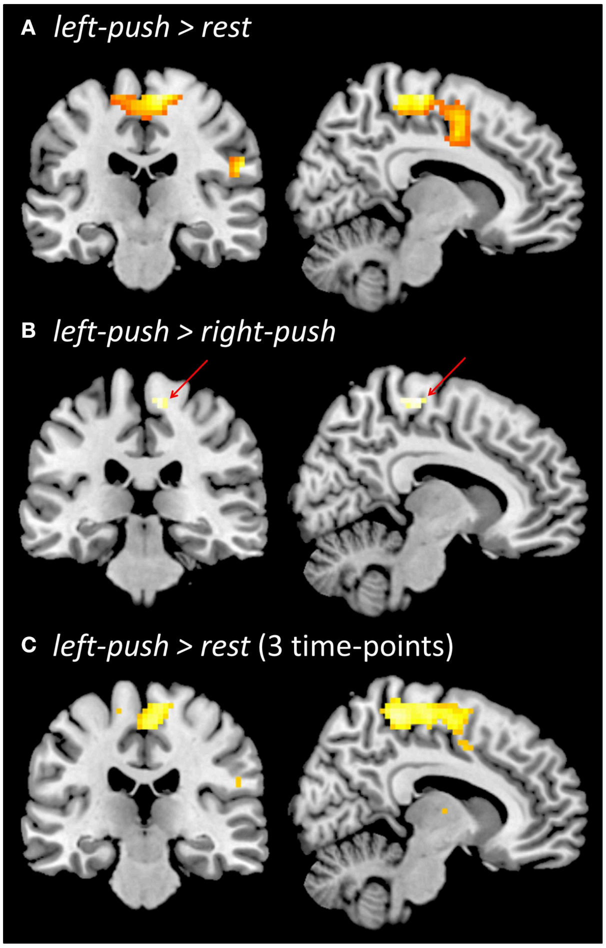

FIGURE 3 | Functional brain activation during pushing one foot onto the horizontal support surface. (A) Localizer prior to experiment, *left-push > rest*. **(B)** Localizer prior to the experiment, *left-push > right-push*. **(C)** During the experiment, across three time-points (baseline, post-local, post-global), *left-push > rest*. All contrasts are thresholded at $p < 0.05$, FWE.

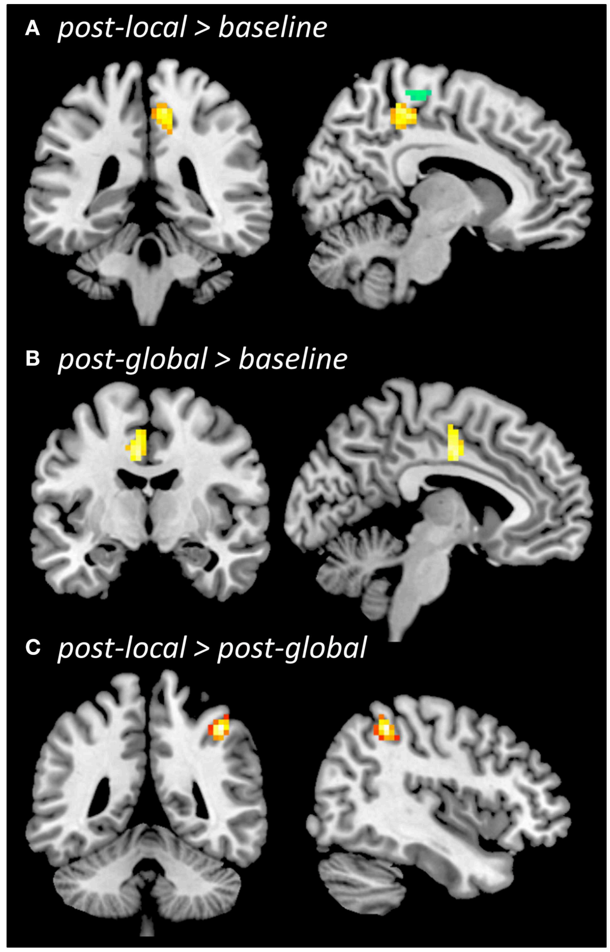

FIGURE 4 | Regional homogeneity (ReHo) during resting state. Whole-brain comparison *post-local > baseline* (**A**, overlaid with functional localizer ROI, *left-push > right-push*), *post-global > baseline* **(B)**, *post-local > post-global* **(C)**, all thresholded at $p < 0.005$ (uncorrected), cluster size $k = 42$. The contrast *post-global > post-local* (not shown) did not reveal significant differences.

functional localizer at the beginning of the experiment, peaking in right medial motor cortex ($p < 0.05$, FWE; 3, −19, 61; 492 voxels; $Z = 5.79$). Comparison of push activation *(left-push > rest)* for each pair of time points showed a significant cluster in the occipital lobe for *post-local > post-global* ($p < 0.005$, $k \geq 42$; −24, −82, 16; 51 voxels; $Z = 3.36$) and in the left temporal lobe for *baseline > post-local* ($p < 0.005$; $k = 42$; −60, −1, −2; 49 voxels; $Z = 3.19$). A ROI-based analysis (based on functional localizer prior to the experiment, *left-push > rest, left-push > right-push*) did not reveal any significant differences of the activation during pushing between the three time points (*baseline, post-local, post-global*).

Resting State Analysis (ReHo)

ReHo increased from *baseline* to *post-local* (**Figure 4A**) in right medial sensorimotor cortex ($p < 0.005$, $k = 42$; 6, −33, 51; $Z = 3.65$; 62 voxels) as well as additional clusters in temporal cortices (see Supplementary Material). The ROI-based analysis showed that ReHo increased in the ROI defined by the functional localizer prior to the experiment [*left-push > rest*: $t_{(20)} = 2.46$, $p = 0.011$; *left-push > right-push*: $t_{(20)} = 1.49$, $p = 0.076$] as well as the activation in the push-trials during the experiment [*left-push > rest*: $t_{(20)} = 2.52$, $p = 0.01$). Decreases in ReHo from *baseline* to *post-local* were found in lateral sensorimotor areas as well as several additional brain areas (see Supplementary Material).

ReHo increased from *baseline* to *post-global* (**Figure 4B**) in left SMA/CMA ($p < 0.005$, $k \geq 42$; −3, −9; $Z = 3.40$; 44 voxels), as well as in additional clusters in left temporal cortex (see Supplementary Material). This increase was significant in one of the ROIs defined by the functional localizer [*left-push > rest*: $t_{(20)} = 1.8$, $p = 0.043$; but *left-push > right-push*: $t_{(20)} = -0.16$, n.s.] and marginally significant in the ROI defined by the pushing-related activation across the three time points during the experiment [*left-push > rest*: $t_{(20)} = 1.48$, $p = 0.077$]. Decreases in ReHo from *baseline* to *post-global* were found in lateral sensorimotor areas (see Supplementary Material).

Comparing ReHo between *post-global* and *post-local* (**Figure 4C**) showed a significant cluster in right lateral motor cortex (*post-local* > *post-global*; $p < 0.005$, $k = 42$; 42, −45, 51; $Z = 4.74$; 46 voxels) and one additional cluster in right temporal cortex (see Supplementary Material). The difference was marginally significant in the ROIs defined by the functional localizer [*left-push* > *rest*: $t_{(20)} = 1.52$, $p = 0.072$, *left-push* > *right-push*: $t_{(20)} = 1.67$, $p = 0.055$] and significant in the ROI defined by the push-activation across the three time points during the experiment [*left-push* > *rest*: $t_{(20)} = 1.96$, $p = 0.032$]. The opposite contrast (*post-global* > *post-local*) did not show any significant differences in the whole-brain or ROI-based analyses.

Subjective Reports

None of the participants reported prior experience with the Feldenkrais method. One participant experienced discomfort while lying in the scanner. Data from this participant (not included in the $N = 21$ above) were excluded from all analyses.

About half of the participants reported changes in subjective experience during performance of the pushing movement after the artificial floor intervention. Among other things, participants described that their "foot felt more relaxed, resulting in more pushing with the ball of the foot rather than just the heel," that "the pushing felt easier," that "it was easier to control the movement," that "the contact area of the foot on the support surface was larger," or that they "generally felt more relaxed" after the intervention. (No distinction was made in the informal interview between the *local* and the *global* intervention). Moreover, several participants reported differences between the left and the right leg during bipedal upright standing (outside the scanner) after the experiment. For instance, participants described the left foot and leg as feeling "lighter but in clearer contact with the floor," having a "wider contact area," feeling "more relaxed" or "more stable, better able to keep balance," compared to the right side.

Discussion

We set out to study potential changes in neural activity during a gentle foot-pushing task (related to body support) and resting state, induced by two forms of the artificial floor intervention: the *local* manipulation, in which the practitioner focuses on mobility within the foot, and the *global* manipulation, in which the practitioner explores the connection from the foot to the rest of the body, focusing on the function of the foot for body support. Both forms of the intervention were carried out with the high interactive quality described in the Introduction, attending and adjusting to minute cues and responses the practitioner perceives visually or haptically during the manipulation. However, the *global* intervention was hypothesized to address a more complex and action-related function (body support) than the *local* intervention (mobility within the foot). We did not observe reliable changes in pushing-related activity in sensorimotor brain regions from pre- to post-intervention. However, resting state activity (quantified by regional homogeneity, ReHo), changed in primary and higher-order motor regions in distinct ways for the two forms of the intervention.

Brain Activity While Pushing with the Foot

Brain activity while gently pushing the foot onto a horizontal support surface (and releasing the push) was measured prior to and during the experiment, as an active motor task hypothesized to be functionally related to the artificial floor intervention. Brain activity was comparable for left-foot pushing across these conditions, including broad areas of primary sensorimotor cortices and higher-level motor areas. Contrasting left- to right-push showed significant differences in right medial primary motor cortex, consistent with somatotopic representation of the foot (Penfield and Boldrey, 1937; Lotze et al., 2000). Brain activity in the pushing-task was used to define ROIs, in order to assess and compare potential changes in brain activity induced by the interventions.

Brain activity during the push task in sensorimotor cortices or in the ROIs defined prior to the experiment was not reliably affected by the artificial floor intervention. Thus, the fMRI measurement does not provide evidence that one or both of the two interventions altered the neural representation of self-generated pushing. In particular, we did not observe the hypothesized more widespread activity after the global intervention. At the same time, the absence of an effect suggests that the pushing action did not reliably differ between the different time points. Hence, differences between conditions found in resting state activity (which was measured after the pushing task) cannot be portrayed as mere after-effects of different ways of active pushing, but instead as consequences of the artificial floor intervention.

Effects of Artificial Floor on Resting State Activity

Significant increases in resting state activity in sensorimotor and higher motor areas were observed after the artificial floor intervention. Moreover, changes from *baseline* (pre-intervention) to *post-local* and *post-global* differed in spatial location. The *local* intervention induced an increased ReHo in right medial primary motor cortex, consistent with somatotopic foot representations found in previous studies (Penfield and Boldrey, 1937; Lotze et al., 2000). In contrast, the *global* intervention induced significant ReHo increases in left SMA/CMA. While these regions are also part of the medial motor regions, activation was more anterior after the *global* intervention than after the *local* intervention, and in the opposite hemisphere. Directly comparing ReHo post-global and post-local showed greater ReHo after the *local* intervention in right lateral primary motor cortex. ReHo in pushing-related ROIs increased relative to *baseline* both after the *local* and the *global* intervention, and the increase tended to be more pronounced *post-local*.

These findings are partly consistent with our predictions. The *local* intervention induced an increase in ReHo in the primary motor cortex representation of the stimulated foot. This suggests a relatively confined, indeed "local," effect of this intervention, which may or may not be specific to the particular technique. For instance it might be a general sensorimotor attention effect, that could potentially also be induced by other forms of tactile stimulation. In contrast, the increase from *baseline* to *post-global* was not localized in primary motor cortex (as for the local intervention) but in a more anterior part of motor cortex

(SMA, CMA) that has been related to higher-level aspects of motor control (Sahyoun et al., 2004; Francis et al., 2009). Moreover, this increase in ReHo was found in the left (ipsilateral) hemisphere, unlikely to be activated by plain tactile stimulation of the left foot. However, directly contrasting resting state activity after the two interventions did not reveal regions with greater ReHo *post-global* relative to *post-local*. Clearly, the processes underlying these changes in resting state activity remain to be investigated in more detail. Yet, the results are in general compatible with the prediction that the *global* intervention would engage more functional, action-related brain networks, while the *local* intervention would engage brain regions representing the stimulated body part.

Limitations, Strengths, and Outlook

As, to our knowledge, elements of the Feldenkrais method have never been investigated neuroscientifically before, this was a highly exploratory study. Yet, the study was aimed at a relatively subtle effect, namely the (hypothesized) differential effect of two ways of performing the artificial floor intervention: *local*, exploring small movements of foot and ankle as a consequence of the touch; and *global*, focusing on the function of the foot for body support. As the study investigated this subtle difference, no "non-Feldenkrais" control condition involving tactile foot stimulation was included in the study design. As a consequence, we cannot rule out the possibility that increased ReHo in primary sensorimotor areas after foot stimulation, as found after the *local* intervention, might be an effect of increased somatosensory attention to the foot (Johansen-Berg et al., 2000).

Unfortunately, our experimental setup did not allow for measurements of the movement of the board, the contact forces and area between board and foot, or the resulting (minimal) movement in the participant's body. In particular, we are unable to report potential differences in these parameters between the *local* and *global* intervention. We can therefore not rule out the possibility that observed differences in ReHo may be explained by systematic differences in low-level parameters of the intervention. Also, the push-forces exerted by the foot on the floor in the active conditions, could not be recorded in the scanner, and we did not assess potential changes in movement patterns after the intervention outside the scanner. Thus, further research is needed to characterize the artificial floor intervention in terms of the physical interaction between board and participant's foot as well as to assess potential effects of the intervention at the motor-behavioral level.

Several methodological strengths of the present study should also be pointed out. Changes in resting state activity were present in ROIs defined by independent functional localizer tasks. While differences in ReHo between conditions were only found with relatively liberal significance thresholds ($p < 0.005$, uncorrected), probability of type-I error was controlled for by requiring an appropriate minimal cluster size determined by Monte Carlo simulation (Ward, 2002). All participants had previous experience with MR studies in order to minimize potential discomfort or distress. Participants were interviewed about potential discomfort after the experiment and the single participant reporting discomfort was excluded from the analysis. Participants had no prior experience with the Feldenkrais method (according to self-report after completion of the experiment) and were naive to the goals of the study. The intervention was carried out by an expert Feldenkrais practitioner (EA). The practitioner was only informed directly before the first intervention about the sequence of conditions to avoid effects this knowledge might have on the initial interaction with the participant.

The artificial floor represents some principles general to the Feldenkrais method, in particular the individualized and interactive nature of manipulations and the focus on functional relationships. The results of the present study indicate that differences in focus on the side of the practitioner, even in the relatively abstract interaction of touching the participant at the foot by means of a planar board, are associated with reliable differences in neural resting state activity. Moreover, despite the fact that the present study used a very minimalistic intervention in a highly constrained experimental setup, several participants reported subjective changes such as a more "relaxed" foot, a larger contact area of the foot on the support surface, increased ease of the pushing movement, or more stability in standing on the leg. While these reported effects are confounded with task repetition, they were mostly specific to the left side (to which the intervention applied) and are consistent with anecdotal reports of experienced practitioners about frequently observed effects of the artificial floor intervention. Typical Feldenkrais sessions last longer (e.g., 30–45 min) than the intervention used here (2×3 min) and involve more body parts and functional relationships between them. For instance, a Feldenkrais session involving the artificial floor manipulation would generally connect the support/push function of the foot more explicitly to the rest of the body, for instance by asking participants to perform related active movements by themselves (such as the pushing movement used in the present study, or getting up to walk a few steps) or by providing additional manual touch and guidance at other parts of the body. Further, studies are needed to investigate potential effects of more complete Feldenkrais interventions on the nervous system as well as subsequent motor behavior.

Conclusions

The results of this exploratory study show that a short, non-intrusive sensorimotor intervention based on the Feldenkrais method can have effects on spontaneous cortical activity in functionally related regions. Moreover, two variants of performing the artificial floor manipulation, focusing on either foot mobility (*local*) or functional use of the foot for body support (*global*), differentially affected subsequent resting state activity. Increased resting state activity in higher-order motor areas supports the hypothesis that the *global* intervention engages action-related neural processes.

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Supplementary Material

The Supplementary Material for this article can be found online at: http://journal.frontiersin.org/article/10.3389/fnhum.2015.00232/abstract

Video S1 | Videos of a Feldenkrais practitioner (EA) performing the artificial floor intervention.

Video S2 | Thresholded statistical parametric maps for the different second-level analyses, for activation during pushing and during resting state (ReHo).

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Conflict of Interest Statement: One of the authors (EA) is a Feldenkrais practitioner and teacher, directing professional training programmes in the Feldenkrais method. One of the authors (JV) took part in one such training but is not working as a practitioner. The other authors are not associated in any way with the Feldenkrais method. The current study does not address the effectiveness as such but investigated the short-term influence of a brief sensorimotor manipulation motivated by the Feldenkrais method. We therefore do not see any actual conflict of interest.

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Ballet as a movement-based contemplative practice? Implications for neuroscientific studies

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There is a rising scientific interest in the neuroscience behind contemplative practices (see e.g., Vago and Silbersweig, 2012 for a review), including movement-based practices such as yoga and tai chi. Given that, it becomes important to ask how such contemplative practices differ from Western movement practices such as dance. In both dance training and contemplative movement, one learns to control the body very precisely, and this requires an assortment of mental skills as well. As a practitioner of both classical ballet and contemplation, and as a neuroscientist who studies contemplation, I will examine how the neural and mental causes and consequences of movement training differ between dance and contemplation. Ballet, rather than modern dance, serves as a good contrast for contemplative practice, because modern dance itself has been influenced substantially by contemplative practice (Hay, 2000). I will compare classical ballet and movement-based contemplative practice on the dimensions of (i) cultivation of attention, (ii) development of interoception, (iii) cultivation of meta-cognition, and (iv) emotion regulation. To date, there are limited studies of movement-based practices, for the obvious reason that movement tends to create artifacts in neuroimaging and EEG measures (e.g., Gwin et al., 2010). I will point out important gaps in our neuroscientific understanding of these phenomena. The results have implications for how we conduct studies of contemplative practitioners and dancers.

CULTIVATION OF ATTENTION

The first thing that happens when engaging in contemplative practice is the cultivation of attention. There is a rich literature on how contemplative practice trains sustained attention (MacLean et al., 2010), attentional stability (e.g., Lutz et al., 2009; van Vugt and Jha, 2011), the ability to deal with conflicting information (Jha et al., 2007), and so on. While most of the research on attention has been done on sitting meditation, embodied practices such as tai chi have been shown to affect attention as well (e.g., Kerr et al., 2008). These behavioral effects are accompanied by specific changes in the brain as well: for example meditation has been associated with an increase in phase-locking to presented stimuli, thought to reflect more selective attention (Lutz et al., 2009), and increased modulation of 7–14 Hz alpha oscillations thought to reflect the direction of attention to relevant inputs (Kerr et al., 2011).

The training in ballet too requires substantial attentional focus, since it involves sustained attention to the details of muscle tension and location of body parts, situational awareness of where the other dancers are, and memorization of movement sequences. Cultivation of focused attention is generally reflected in a strengthening of the fronto-parietal attention network that consists of most importantly the intraparietal sulcus, medial frontal gyrus, inferior frontal gyrus, and anterior cingulate cortex (Corbetta and Shulman, 2002; Dosenbach et al., 2007). It would therefore be interesting to compare the developmental trajectory of fronto-parietal attention network use over the course of dance and contemplative training, which both require thousands of dedicated hours of practice (Slagter et al., 2011). In fact, changes in dedicated neural circuits are already slowly starting to be uncovered (see e.g., Lazar et al., 2005; Hänggi et al., 2010 for reports of brain structure changes in meditators and dancers, respectively).

INTEROCEPTION

There has been some controversy on whether contemplation helps to improve interoception. Interoception refers to the ability to feel your body. It is measured in tasks such as the counting of heartbeats. It may not be improved very much by contemplative practices that emphasize sitting still (Khalsa et al., 2008; Sze et al., 2010; Daubenmier et al., 2013), but there is some evidence that it does improve in practitioners of tai chi (Kerr et al., 2008). This is interesting, because improvements in awareness of the outer body have been associated with improvements in motor control (e.g., Wong et al., 2012). Moreover, long-term meditation practice has been associated with, among other things, increased cortical thickness in the right anterior insula (Lazar et al., 2005), a brain structure crucial for interoception (Critchley et al., 2004) (note that this was found in a group of Vipassana meditators, who focus a lot on sensations of breathing in their practice).

Based on these findings, one could imagine that ballet dancers, who are preoccupied with their body all day, have a good sense of interoception. However, an equally likely hypothesis is that dancer's interoception is not different from the general public, since ballet dancers judge the shape of most of their movement in mirrors and are trained to ignore pain signals from their bodies since "the show must go on." (McEwen and Young, 2011).

Many ballet dancers even feel the need to resort to yoga, gyrokinesis, or pilates to attune themselves to their bodies again. In contrast, contemporary dancers typically work without mirrors, and focus more on interoceptive signals.

Consequently, I predict that there is a clear difference between dance forms in the extent to which interoception is developed. Since in classical ballet, dancers tend to rely more on mirrors to correct their position and create the desired shapes with their body, I predict classical dancers have an interoceptive accuracy not different from non-dancers, while for modern dancers, who tend to rely less on mirrors, there should be superior interoceptive accuracy compared to non-dancers. One study that investigated the relationship between interoceptive accuracy (in that case, for emotions) in both dancers and meditators showed that meditators were the most accurate, followed by dancers, who were still more accurate than participants from the general population (Sze et al., 2010). However, this study did not separate modern from classical dancers. Studies of the neural circuitry underlying interoception in dancers are missing altogether. So, even though interoception is likely to be trained in both dance and contemplation, the jury is still out.

META-COGNITION

A third mechanism that is crucial for both dance and contemplation is meta-cognition. Meta-cognition could be defined as a process of re-describing its knowledge to yourself and comparing it to predictions you have made (Timmermans et al., 2012). In other words, meta-cognition involves observing your own thoughts. Meta-cognition is crucial for monitoring of whether your cognitive processes are developing along the lines you intend to (for example: are you paying attention to that letter on the screen, or are you day-dreaming about what to have for lunch?), and if necessary adjusting them. For ballet dancers, meta-cognition is necessary for checking whether their attention is divided appropriately between monitoring the use of the correct muscles, monitoring the location of fellow dancers, thinking ahead in the memorized movement sequence, and often also creeping in the skin of the character or emotion they are trying to convey.

In contemplation too, meta-cognition is crucial (Kuan, 2012). Meta-cognition helps the yogi to check the alignment of their body, and observe their thoughts and emotions as those unfold, making sure not to get caught up in them. Rather than simply mindlessly performing movements, there is an emphasis on observing how movement affects the body and mind. In addition, meta-cognition is necessary to observe the appropriate balance between tensing and relaxing (e.g., Wallace, 2008). While meta-cognition has not been specifically investigated in the context of movement-based practices, it has in general been associated with BOLD activity in the dorso-medial prefrontal cortex and the anterior insula (Schilbach et al., 2012). In more cognitive tasks, meta-cognition appears to rely more on lateral prefrontal cortex and anterior cingulate cortex (Fox and Christoff, 2014). This is consistent with the idea that a crucial determinant of meta-cognition is working memory capacity. Working memory strategies are what allows the meta-cognitive processes to maintain multiple pieces of information simultaneously and to transform those for alternative needs, e.g., simultaneously maintaining the location of fellow dancers with the memorized sequence of steps.

Interestingly, while ballet dancers tend to use meta-cognition to ensure that they are still delivering the correct product (dance) to the audience, contemplatives use meta-cognition to primarily observe their own mental state. The meta-cognition that dancers use, in view of a project delivery is typically highly critical and judgmental, while yogis train to observe their mind and body with a non-judgmental attitude. It could even be said that an important function of meta-cognition in contemplation is monitoring whether or not one is reacting judgmentally. Consequently, comparing dancers and contemplatives on meta-cognition would be an interesting way to isolate externally-directed from internally-directed meta-cognition. Moreover, it will be interesting to see whether those two types of meta-cognition are associated with different neural correlates, along the lines of the suggested difference between meta-cognition of emotions and bodily state versus cognitive states (Fox and Christoff, 2014).

EMOTION REGULATION

Emotion regulation is an umbrella term for many processes that serve to influence emotions and align them with ones goals (Todd et al., 2012). It includes reappraisal of events, suppression of emotional reactions, avoidance, coping, and more. An important part of training in many contemplative practices, including movement-based contemplative practices involves techniques of dealing with emotions that could be classified as emotion regulation. Specifically, practitioners cultivate the ability to observe emotions but withhold automatic elaboration and action tendencies that flow from these emotions. Many contemplative practices also have an element of dealing with emotions by refocusing attention on a different stimulus, such as the breath or physical sensations. Not surprisingly then, yoga has been used in the treatment of war veterans with Post-Traumatic Stress Disorder (da Silva et al., 2009). Some regions that are important for emotion regulation, the lateral prefrontal cortex and orbitofrontal cortex, have been shown to have larger activity and density in meditators (e.g., Farb et al., 2007; Hölzel et al., 2008; Grant et al., 2010). These areas are thought to be engaged in emotion regulation by modulating activity in areas such as the amygdala, striatum, and hippocampus (see Vago and Silbersweig, 2012 for a discussion).

Yet I argue that ballet training too, involves some cultivation of emotion regulation skills. Many professional and non-professional dancers describe their dancing as a way to express their emotions, as a kind of catharsis, which is in fact controlled enhancement of emotions (Ochsner et al., 2004). Not surprisingly, many types of dance therapy have been developed to deal with emotional turmoil (e.g., Betty, 2013). I predict that dance therapy and sustained training in dance modulate the connectivity between lateral prefrontal cortex and orbitofrontal cortex on the one hand and the amygdala and hippocampus on the other.

On the other hand, we should also note a crucial difference in the way emotions are experienced in ballet versus contemplative movement practices. While in dance, particularly in theatrical performance, the goal is to experience emotions to the fullest, in contemplative practices emotions are seen as merely an expression of the mind that arises but also disappears again. One could say, in dance emotions are magnified and objectified, while in contemplative practice, the fleeting nature of emotions is emphasized, which actually makes them decrease in magnitude and importance. Recently, it has been suggested that the "stickiness" of emotions is accompanied by a prolonged response in the amygdala (Schuyler et al., 2014). If this is true, this amygdala response should be increased in dancers relative to contemplative practitioners (but note that more regions than just the amygdala are involved in producing the full-blown experience of emotions; Anderson and Phelps, 2002). So, while professional dancers and contemplatives both work on adapting and regulating their emotions, they do this in different ways.

SYNTHESIS AND FUTURE DIRECTIONS

I have shown how there are many commonalities between classical ballet and contemplative movement practices, in the domains of attention training, interoception, meta-cognition and emotion regulation. Yet, ballet training and contemplation also differ in the presence of a non-judgmental attitude and importance given to emotions.

While the behavioral correlates are relatively well-described, the neural pathways remain under-explored. Furthermore, these commonalities and differences between dance and contemplative movement practices could have implications for the studies we do. For example, using ballet dancers as a control group for long-term contemplative practitioners could be very interesting, because both populations have developed a strong focus on their craft over a life-time of concentrated practice, and developed skills in the domain of attention, meta-cognition, interoception, and emotion regulation. In contrast, the groups differ in their non-judgmental attitude and solidity ascribed to emotions. Comparing these groups therefore allows one to tease apart the judgmental and non-judgmental modes of attention, meta-cognition, and emotion regulation, and could thereby help define its neural and behavioral correlates.

In addition, it would be interesting to engage dancers and practitioners of contemplative movement practices together in neurophenomenological experiments. Neurophenomenology (Varela, 1996; Cosmelli and Thompson, 2007) involves analyses of brain activity informed by disciplined introspection on the part of the participants. Since both of these groups of people have spent considerable time observing and honing their bodies and minds, such experiments could help to elucidate the detailed mechanisms behind these types of training, as well as the time course of the arising of judgmental attitudes.

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