THE EFFECT OF MEDITATION ON AWARENESS AND REGULATION OF INTERNAL BODY STATES

by

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CHAPTER 1. INTRODUCTION

1.1 Meditation

Meditation is a form of mental training that has been practiced for thousands of years, and that can be conceptualized as a family of complex emotional and attentional regulatory training regimens developed for various ends, including the cultivation of well being and emotional balance (Davidson et al., 1976; Ekman, 2005; Lutz, 2007). Meditation has also been defined as involving a process of intentional self-regulation of attention, in which attention is directed from a combination of external and internal stimuli to a primarily internally perceptive state (Astin et al., 2003; Bonadonna, 2003). Traditional philosophies emphasize that anyone can learn to meditate (Taimni, 1961), and that through repeated practice meditation provides long-term effects that outlast the confines of individual meditative states (Ahir, 1999; Burley, 2000; Nyanaponika, 1969).

Although typically practiced in the context of spiritual traditions, there has been a notable increase in the therapeutic application of meditation as a complement in alternative medicine (Arias et al., 2006; Astin et al., 2003; Barnes et al., 2004a). It has been estimated that nearly half of all adults in the United States have used some form of complementary and alternative medicine (CAM) within their lifetime (Barnes et al., 2004a). Meditation, yoga, and deep breathing comprise a total of 24.3% of all CAM usage (Barnes et al., 2004a), and when included under the umbrella term of 'Mind-body medicine' (which excludes prayer), represents the second most commonly used CAM technique.

The efficacy of meditation training in influencing the course of a variety of physical and mental disorders is under increasing investigation. Meditation training

(primarily via Transcendental Meditation and Mindfulness Based Stress Reduction (Kabat-Zinn, 1990)) has been reported to be beneficial in the treatment of anxiety disorders (Kabat-Zinn et al., 1992; Miller et al., 1995), depression (Teasdale, 2000), hypertension (Anderson et al., 2008), substance abuse (Bowen et al., 2006; Bowen et al., 2007; Davis et al., 2007), binge eating (Kristeller, 1999), chronic pain (Kabat-Zinn et al., 1985), cancer (Carlson et al., 2003; Carlson et al., 2004), and in the facilitation of immune responses (Carlson et al., 2007; Davidson et al., 2003). However, despite an increasing utilization of meditation in clinical settings and increased investigations of the effects of meditation, a recent survey of the available literature concluded that there was limited evidence for the efficacy of meditation as an adjuvant in medicine (Ospina et al., 2007). The lack of evidence was linked primarily to the poor methodological quality of extant studies, such as the use of biased and nonstandardized methods, the lack of randomized controlled trials capable of making causal inferences, as well as disparate conceptualizations of the meditation practice.

Most meditation traditions incorporate attention to internal body sensations as a component of the practice, particularly in the beginning stages of instruction, possibly because the availability of these sensations from moment to moment makes them a convenient object to focus on. The most commonly attended body sensations include the breath, the position of the joints (proprioception), the degree of muscle tension, and the heartbeat (Kabat-Zinn, 1990; Kornfield, 1996; Nairn, 2000; Selby, 1992). Although attention to internal body sensations is most commonly practiced under conditions of rest, the subjective experiences of these body sensations are also routinely modulated through manipulations of the breath and musculoskeletal posture, particularly during the practice

of yoga exercises (Arambula et al., 2001; Bhajan Y, 2000; Peng et al., 2004). Many meditation traditions state that the repeated practice of attending to internal body sensations results in enhanced awareness of these sensations, and further assert that the meditation practice results in enhanced awareness of a variety of other internal events, such as the ongoing experience of thoughts and emotions (Hart, 1987; Kabat-Zinn, 1990; Kornfield, 1996; Nairn, 2000). Many traditions also teach that the practice results in an ability to regulate (increase and decrease) physical and mental states including, for example, levels of physiological arousal, and the experience of positively and negatively valenced emotional states and traits (Ekman, 2005; Kabat-Zinn, 1990; Kornfield, 1996; Nairn, 2000).

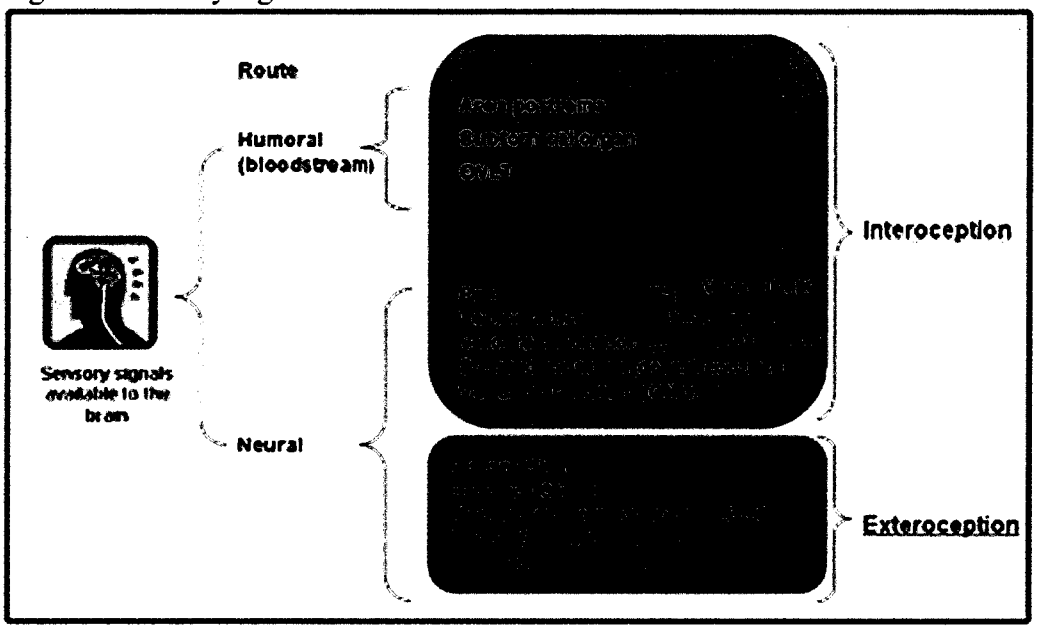
1.2 Interoception

The study of internal body sensations date back more than 100 years, to when Sherrington coined the term 'interoceptor' in reference to receptors for signals originating inside of the body (Sherrington, 1961; Cameron, 2001). Interoception is broadly defined as the perception of stimuli originating inside of the body, and is defined in contrast with exteroception, which refers to perception of stimuli originating outside of the body (such as lights or sounds). Interoception encompasses a variety of sensations, including those arising from the viscera (such as the feeling of the heartbeat, the breath and gastrointestinal sensations), the musculoskeletal and vestibular systems (such as proprioception and gravity perception), the skin (for example, flushing of the skin and itching), and a host of chemical, endocrine and osmotic changes that arise from within the blood (such as feelings related to thirst and hunger) (Cameron, 2001; Craig, 2002;

Critchley et al., 2004; Damasio, 2003; Khalsa et al., In press; Mayer et al., 2006; Pollatos et al., 2007a; Vaitl, 1996). Many of these signals are a part of the organism's daily homeostatic operations and exert their effects below the level of consciousness. At the same time, several interoceptive signals can be perceived at the conscious level, as anyone who has ever gone hungry (or, conversely, had too much to eat), felt their heart pounding after running up a few flights of stairs, or waited too long before urinating can tell you.

Recent evidence has shed light on the neuroanatomical structures interoceptive signals use to reach the brain. These include chemosensitive areas of the central nervous system (e.g. area postrema, organum vasculosum of the lamina terminalis, and the subfornical organs), proprioceptive and vestibular systems, C and A delta fibers of the lamina I spinothalamic pathway (informing pain, temperature and mechanosensation), and visceral sensation primarily subserved by vagal afferents (**Figure 1**) (Craig, 2002; Saper, 2002). Interoceptive signals are continuously relayed from the periphery to key structures in the brainstem (importantly the nucleus of the solitary tract and the parabrachial nucleus), to the hypothalamus, and through the thalamus (particularly the ventromedial posterior nuclei) where they are proposed to be mapped and re-represented in several regions of the cortex, including classic somatosensory cortices (SI and particularly SII), visceral sensory cortex (the insula), cingulate cortex (particularly the anterior cingulate) and ventromedial prefrontal cortex (Craig, 2002; Damasio, 2003).

Figure 1. Sensory signals available to the brain.



Red areas denote interoceptive signals and transmitting structures. Blue areas denote exteroceptive signals and transmitting structures. OVLT: organum vasculosum of the lamina terminalis; CN: cranial nerve; DRG: dorsal root ganglion (figure adapted from Damasio, 2003).

1.3 Interoception and emotion

Interoceptive sensations have also occupied a central role in classic and contemporary theories of emotion. In *The Expression of Emotion in Man and Animals*, Charles Darwin (Darwin, 1872) highlighted the involvement of sensations from the viscera in his description of the experience of fear, noting "the heart beats quickly and violently, so that it palpitates or knocks against the ribs" and that "in connection with the disturbed action of the heart the breathing is hurried." The subsequent highly influential "James-Lange" theory of emotion, put forth independently by William James (1884) and Carl Lange (1885), posits that signals originating from the within the body, such as the sensation of the heartbeat and breath, are fundamental for the experience of emotion to

the extent that "the feeling of bodily changes as they occur IS the emotion," and that in the absence of the experience of bodily change all that is left is a "cold and neutral state of intellectual perception" (James, 1884). Since the inception of the James-Lange theory, the role of afferent bodily sensation in emotion has been debated. Against the James-Lange "peripherist" theory, Walter Cannon (1929) and Philip Bard (1928) defended a "centralist" theory of emotion, arguing that the full range of visceral sensations was neither a necessary nor a sufficient condition for the experience of emotion. This was based on observations of intact emotional expression in deafferented cats, intact emotional experience in humans with spinal cord transections, and the absence of genuine reports of emotional experience in humans following sympathetic modulation of visceral sensations with adrenaline (Marañon, 1924). Stanley Schacter and Jerome Singer endorsed a similar view in their "attribution theory" (Reisenzein, 1983; Schacter, 1962), based on studies of epinephrine injections in humans. The theory stated that the subjective perception of physiological arousal, although often a component of the experience of emotion, was not sufficient to elicit specific emotional states. Emotions required an additional cognitive process of attribution of meaning to the perceived physiological response, based on available contextual cues.

Contemporary views however continue to highlight the importance of peripheral sensations in the subjective experience of emotion. Beyond support for a general relationship between physiological and subjective arousal it has been suggested that specific patterns of signals within the body, triggered by emotionally competent stimuli and under the control of complex patterns of neural and humoral signaling, could provide a basis for differentiating emotions (Damasio, 1994; Damasio, 1999). More generally,

patterns of activity in a network of body-sensitive brain regions are thought to underlie the experience of different emotions (Damasio, 1994; Damasio, 1999; Damasio, 2004; Damasio et al., 2000). An essential component of feelings, defined as the subjective experience of emotion, could be characterized by the perception of bodily changes mediated by these brain regions (Damasio, 1994; Damasio, 1999; Rainville et al., 2006). Functional neuroimaging studies have provided some preliminary support for this view, demonstrating the activation of viscerosensory and somatosensory brain regions such as the insula, the somatosensory cortices and the anterior cingulate cortex during the feeling of a wide range of emotions (Blood and Zatorre, 2001; Critchley et al., 2001; Damasio et al., 2000; Lane et al., 1997; Mayberg et al., 1999; Reiman et al., 1997). However, the precise role of body-sensitive brain regions in emotion remains a controversial and very much unresolved topic, and other views of emotion have emphasized the roles that other brain regions play in encoding and evaluating the reward and punishment values of different stimuli in order to maximize appropriate environmental response selection (Rolls, 2000).

In summary, meditation can be commonly conceptualized as a set of training regimens that are purported to result in enhanced bodily awareness and also to facilitate attentional and emotional regulatory capacities. Although there is a widespread notion in the public domain (vis a vis meditation traditions) that increased interoceptive awareness develops through the practice of meditation, no studies have systematically examined whether there is empirical support for this possibility.

CHAPTER 2. PREVIOUS STUDIES OF MEDITATION

2.1 Approaches to studying meditation

Studies investigating the effects of meditation can be separated into two general categories: those employing a longitudinal design and those employing a cross sectional design. In the longitudinal design, meditation-naïve individuals are recruited and a portion are randomly assigned to be trained in the practice of meditation while the rest are assigned to a control condition. In the cross sectional design, meditators of varying experience levels are recruited and compared against individuals with either minimal or zero meditation training (so called nonmeditators). Meditation studies can be further stratified according to those investigating effects occurring during the actual practice of meditation (termed state effects) and those investigating the longer term consequences of meditation that might persist beyond the meditative practice (termed trait effects). A final classification relates to the particular type of meditative tradition under investigation. It is important to note that a multitude of meditative traditions exist, and there are numerous variations even in the approach to the studying meditation within each tradition (Lutz, 2007).

The majority of early studies have employed cross sectional investigations of the state effects of meditation. This is based on a perspective that the likelihood of determining the effects of meditation are maximized while observing experienced participants during the meditation practice, as well as a pragmatic approach that recognizes the challenges involved in specifying the minimum amount of training necessary to observe a hypothetical effect. However, the recent increase in public utilization of meditation techniques, combined with a surge in scientific interest in

examining the effects of meditation (Barinaga, 2003), are likely to result in an influx of studies that utilize the more powerful longitudinal design and incorporate both state and trait approaches.

2.2 Meditation and autonomic function

A central tenet of early investigations into the effects of meditation has been based on the idea that meditation induces a physiologically quiescent bodily state. This was based on initial reports of decreases in autonomic parameters such as heart rate, respiratory rate, blood pressure, skin conductance, and adrenergic reactivity, as well as increased levels of alpha activity in the electroencephalogram during the practice of meditation (mostly Transcendental Meditation (TM)) (Aftanas and Golosheykin, 2005; Aftanas and Golocheikine, 2002; Beary and Benson, 1974; Farrow and Hebert, 1982; Hoffman et al., 1982; Jevning et al., 1992; Orme-Johnson, 1973; Travis and Wallace, 1997; Wallace et al., 1971). Early researchers described this pattern of autonomic responses as an integrated 'relaxation response' (Benson et al., 1974). Four essential components were proposed to be essential for the proper elicitation of this response: (1) An attentional focus in order to minimize distraction (e.g., silent repetition of a word, sound, or gaze fixation). (2) A passive attitude (e.g., lack of concern over performance and redirection of attention following distraction). (3) Reduced muscle tone (facilitated by a relaxed posture). (4) A quiet environment. An additional but not required component included the instruction to close the eyes during the practice (Beary and Benson, 1974). It was emphasized that this response was not restricted to any specific meditation technique or tradition, and that it occurred in the majority of meditation traditions. Furthermore, this

response could be taught outside of the boundaries of formal meditation training, and following training could be generated within a short duration of time (minutes).

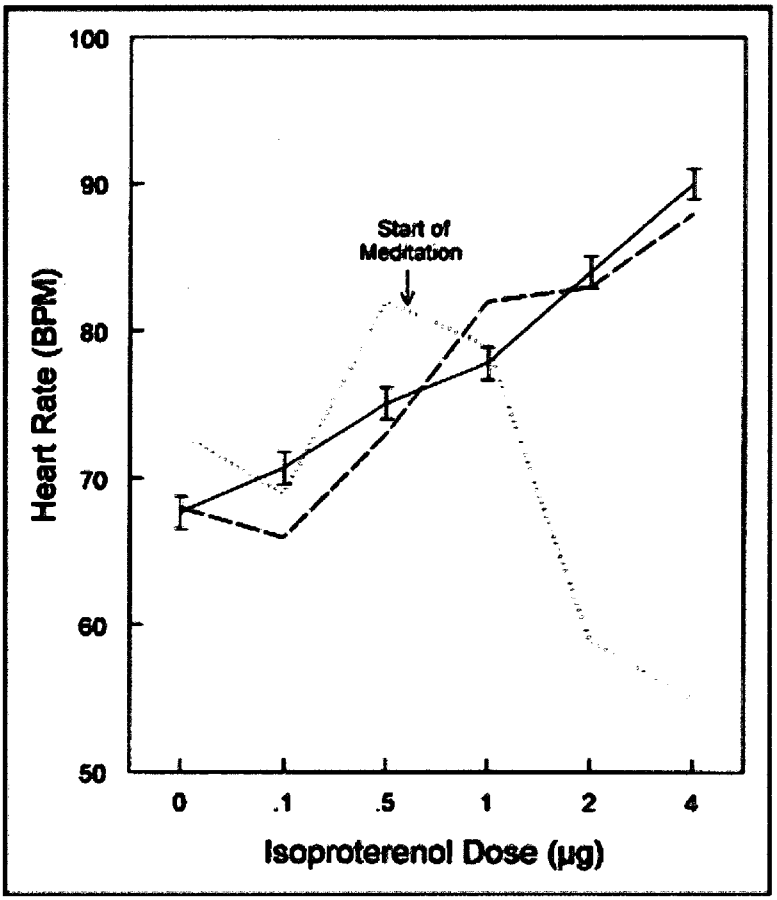
Recent investigations continue to report that reductions in physiological parameters such as heart rate and blood pressure occur during the acute meditation practice (Barnes et al., 1999; Solberg et al., 2004; Telles et al., 1995) as well as following practice over longer periods of time (Barnes et al., 2004b; Barnes et al., 2004c; Harinath et al., 2004). However, a more detailed analysis of autonomic patterns has also shown that meditative states do not simply 'quiet' the body but can in fact alter the variability and complexity of the breath and heart rate, hinting at more dynamic processes underlying these states. For example, greater increases in heart rate variability have been observed during the practice of specific meditations as compared to relaxation techniques (Cysarz and Bussing, 2005; Ditto et al., 2006; Peng et al., 2004; Peng et al., 1999). These differences in heart rate variability have been attributed to exaggerations in respiratory sinus arrhythmia, and are generally thought to be related to the alterations in breathing pattern known to occur during the practice of a variety of different types of meditation (e.g., slow deep breathing vs. rapid shallow breathing, symmetric vs. asymmetric inhalation/exhalation, vocal vs. silent) (Bernardi et al., 2001; Bhajan Y, 2000; Lehrer et al., 1999)

Although the notion that meditation results in physiologically quiescent states is well established, the extent to which meditative practices exert such effects is unknown. Early investigations of yogis in India who claimed to be able to exert considerable voluntary control of the heart (some claimed to be able to stop the heart) revealed limited support for this idea. At best, some individuals were able to exert transient bradycardia,

or reductions in heart rate by engaging in combinations of posture manipulation, muscular contraction and breath holding (including the Valsalva maneuver, or 'bearing down', which elicits a complex pattern of reflexes including tachy/bradycardia and hyper/hypotension) (Wenger, 1961). Subsequent studies have reported mixed results, primarily for different yoga adepts (Fenz and Plapp, 1970; Kothari et al., 1973). More recently, shorter term changes in the ability to reduce the resting heart rate have been reported (Telles et al., 2004). The perception that meditation and yoga confers an increased cardiac regulatory capability has persisted, perhaps in part due to this heterogeneous literature. This notion was recently extended by a study that suggested a novel effect of meditation on the ability to regulate increased levels of cardiovascular arousal. Dimsdale & Mills (2002) reported a case study in which a female meditator was randomly recruited to participate in a standardized isoproterenol challenge as a control subject in their studies of sympathetic nervous system regulation in hypertension (Dimsdale et al., 1988; Mills et al., 1998). Isoproterenol stimulates beta 1 and beta 2 adrengergic receptors equally, and when administered intravenously results in rapid and transient increases in heart rate, contractility and bronchodilation, as well as decreases in diastolic blood pressure. The protocol called for administration of a standard isoproterenol sensitivity test, involving sequentially increasing doses of intravenous isoproterenol. Halfway into the infusions the woman spontaneously decided to start meditating, and continued to meditate during the infusions. At the time of the isoproterenol challenge the investigators did not know she was a meditator, but noticed afterwards that after the fourth dose her heart rate had begun to decrease, in stark contrast to the expected increase. They report that at the highest dose, when the expected heart

rate response was a 21 beats per minute (bpm) increase above baseline, they observed a 17 bpm decrease below baseline (**Figure 2**). Suspecting that the meditation practice had interfered with the isoproterenol response, she was asked to return two weeks later and repeat the challenge, with explicit instructions to avoid meditating. Her heart rate response to the subsequent infusion protocol this time appeared entirely consistent with

Figure 2. Effect of meditation on heart rate response to isoproterenol.



Solid line: mean +/- SE response to isoproterenol in 93 women; *dotted line*, patient's response while mediating; *dashed line*, patient's response when instructed not to meditate. BPM=beats per minute. (Figure and caption reproduced from figure 1, Dimsdale & Mills, 2002).

the typical laboratory response to isoproterenol at rest (i.e. an approximately 20 bpm increase above baseline at the highest dose). This individual reported a self taught meditation practice for many years (though she reported no formal training; no additional practice information was provided), and that she did not practice any particular tradition of meditation. Although this result hints that the practice of meditation may reduce the cardiovascular response to acute physiological arousal, given the history of findings in this area further study is warranted at the group level, in more formally trained meditators with at least several years of experience.

2.3 Meditation and cognitive function

Beyond autonomic function, meditation is hypothesized to exert a host of influences at the cognitive level. Meditation training is commonly thought to facilitate the self regulation of attentional processes and improve emotion regulation, and an increasing number of studies are examining the influence of meditation on these capacities in healthy as well as disease states (Lutz, 2007).

Studies of experienced meditators have suggested that meditation results in an increased attentional capacity. A particularly well designed longitudinal study found that experienced Vipassana meditators demonstrated a smaller attentional blink (a measure of attentional resource allocation) following 3 months of intensive meditation training (Slagter et al., 2007), and that this increased attentional capacity was associated with a reduction in neural measures of resource allocation. Another study found that Tibetan Buddhist monks displayed a prolonged attentional focus in binocular rivalry (a measure of the stability of visual perception) as compared to nonmeditators. Furthermore, 8 weeks

of training in Mindfulness Based Stress Reduction (MBSR, (Kabat-Zinn, 1990)) and as little as 5 days of training in meditation naïve individuals have been linked to modifications in subsystems of attention such as improved orienting and alerting (Jha et al., 2007) and conflict monitoring (Tang et al., 2007), suggesting that the effects of meditation training on attention may not be limited to prolonged and intensive training.

2.4 Neural systems supporting meditation

Early investigations of the neural correlates of meditation drew heavily upon electroencephalogram (EEG) methodologies. Of the numerous studies that have been conducted, the primary findings relate to increases in theta and alpha band power during the practice of meditation (see (Cahn, 2006) for a detailed summary). These increases have further supported the generalized notion that mediation is associated with physiologically quiescent states. However, in contrast with the original descriptions of reduced neural activity, dynamic increases in the pattern of neural activity have also been reported during meditation (Lutz et al., 2004), suggesting that meditative states confer more complex alterations in brain states than originally supposed.

Functional neuroimaging techniques such as Positron Emission Tomography (PET) and functional Magnetic Resonance Imaging (fMRI) provide information about the metabolic rate and blood oxygenation levels of brain tissue, with a high degree of spatial resolution and a moderate degree of temporal resolution. Functional neuroimaging studies of meditation have studied individuals primarily during the act of meditation (Brefczynski-Lewis et al., 2007; Farb, 2007; Holzel et al., 2007; Kjaer et al., 2002; Lazar et al., 2000; Lou et al., 1999; Lutz, 2004). These studies have examined different types of

meditators, such as those practicing Buddhist meditation (including Vipassana), Kundalini meditation, Yoga Nidra, and Mindfulness Based Stress Reduction, a secularly taught form of meditation with roots in the Buddhist contemplative tradition (Kabat-Zinn, 1990). Each of these meditation paradigms involved different tasks, from repetition of a mantra (Lazar et al., 2000; Lou et al., 1999), to continuous fixation of attention on a sensory stimulus such as the breath (Farb, 2007; Holzel et al., 2007) or a visual object (Brefczynski-Lewis et al., 2007), to the generation of states of "unconditional" positive affect (Lutz, 2004) as well as the conscious withdrawal of affect (Kjaer et al., 2002). In each study different control tasks were used for subtraction analyses of brain activity, making it difficult to generalize from the results of the individual study conclusions. Lazar et al (2000) found that sequential practice of a Kundalini meditation protocol progressively enhanced activation in the same regions (most strongly in the middle frontal gyrus and superior parietal lobule), suggesting the possibility of additive effects in discrete neural structures. Kjaer et al (2002) reported increased endogenous dopamine release in the ventral striatum, a region that receives afferents from ventromedial prefrontal cortex, in participants during Yoga Nidra practice. This is the first study to investigate a modulatory role of meditative states at the neuropharmacological level. Preliminary studies of beginning and experienced Buddhist meditators and MBSR practitioners report common activations in body sensitive brain regions including the thalamus, the secondary somatosensory cortex, the anterior cingulate and the insula (Brefczynski-Lewis et al., 2007; Farb, 2007; Holzel et al., 2007; Lutz, 2004). Compared to novices, experienced Buddhist meditators have demonstrated more prominent increases in the right insula and caudate during a meditation involving generation of

states of "unconditional" positive affect (Lutz, 2004) as well as in the right insula and medial frontal gyrus during a meditation involving concentration on a visual object (Brefczynski-Lewis et al., 2007).

Structural neuroimaging studies examine whether differences in macroscopic brain morphology are related to behavioral phenomenon. There is ample cellular evidence to suggest that changes in the response properties of individual neurons occur in response to modifications of sensorimotor input from the periphery (Blake et al., 2002), and functional imaging studies have corroborated these findings at the population level, via changes in the extent of spatial and temporal activation for complex sensorimotor training tasks (Floyer-Lea and Matthews, 2005; Hund-Georgiadis and von Cramon, 1999; Karni et al., 1998). Structural neuroimaging evidence has also suggested that differences in brain structure can be associated with intensive periods of training. For example, increases in cortical thickness of higher order visual areas have been found to occur as a result of intensive juggling training (Draganski et al., 2004), and increased thickness of auditory and motor cortex have been observed in professional musicians compared to nonmusicians (Bermudez and Zatorre, 2005; Gaser and Schlaug, 2003). In a similar vein, preliminary studies of experienced meditators and nonmeditators are finding some evidence for structural neuroanatomical differences. Vipassana meditators have demonstrated increased regional gray matter thickness in the right anterior insula (Holzel, 2008; Lazar et al., 2005) and right hippocampus (Holzel, 2008), brain regions that have shown preferential activation during the practice of meditation (Farb, 2007; Holzel et al., 2007; Lazar et al., 2000; Lou et al., 1999). In addition, meditation has been associated with neuroprotective effects based on the reported absence of age related decreases in

cortical thickness in specific regions including the putamen (Pagnoni and Cekic, 2007) and superior frontal sulci (Lazar et al., 2005).

In the face of such profound differences in methodology and meditation technique under investigation, it is not surprising that each of the aforementioned studies report somewhat different patterns of findings. For example, it remains unclear whether these apparent differences in body and brain states are specific to the tradition practiced or even whether they vary as a function of meditative states within each tradition, as no systematic investigations have focused on this topic. At a holistic level these studies provide initial clues about the networks of brain regions that may be involved in generating meditative states. These studies also suggest the involvement of visceral sensory brain regions in the practice of meditation, further warranting a careful delineation of the relationship between meditation and interoceptive awareness.

CHAPTER 3. OBJECTIVES AND HYPOTHESES

The idea that a meditation practice would lead to enhanced bodily awareness and/or an ability to regulate increased levels of physiological arousal is certainly plausible, but there has been limited scientific evidence to support these claims. Considering the widespread utilization of meditative techniques, an adequate characterization of the effects of the meditation practice is warranted. In the current project, I have aimed to address these knowledge gaps through a series of cross sectional studies examining interoceptive awareness and the ability to regulate interoceptive body states, in several different groups of meditators and nonmeditators. On the basis of previous investigations two overarching hypotheses can be formulated.

The first hypothesis is that the long term practice of meditation is associated with an increase in interoceptive awareness. This hypothesis is derived from the strong emphasis placed on cultivating interoceptive sensations in the majority of meditation traditions, and from the notion articulated within many traditions that the practice of meditation confers increased interoceptive awareness. This hypothesis also stems from preliminary neuroimaging studies that associate the practice of meditation with altered brain structure and differential activation of visceral sensory brain regions.

To test Hypothesis #1, in the first study (Chapter 4), I used the standard method of assessing interoceptive awareness, viz., heartbeat detection, in experienced meditators and nonmeditators. I predicted that meditators would display greater accuracy than nonmeditators on this task. Support for this prediction would come from increased group accuracy rates and increased numbers of accurate heartbeat detectors on the part of the meditators. As it turned out, this approach yielded a negative outcome. However, I was

not convinced by this result because only a minority of all participants were accurate heartbeat detectors. This is a limitation common to all heartbeat detection tasks, which prompted me to develop a new method for assessing interoceptive awareness, using isoproterenol infusions (Chapter 5). I predicted that increased ratings of heartbeat and breathing sensations (indexed by a variety of retrospective and online measures) would occur at increasing doses of isoproterenol, and that at the highest doses the majority of participants would report feeling increases in these interoceptive sensations. This was precisely what I observed. Furthermore, I was able to demonstrate increases in interoceptive awareness in all participants at the highest dose, overcoming the limitations of heartbeat detection tasks. I returned to a test of Hypothesis #1 in Chapter 6, where I used the newly developed isoproterenol method to evaluate interoceptive awareness in experienced meditators and nonmeditators. I predicted that experienced meditators would display increased interoceptive awareness at lower doses of isoproterenol than nonmeditators, as indexed by the same retrospective and online measures utilized previously. I also predicted that, at doses for which the majority of participants generated awareness, meditators would be more accurate at tracking their ongoing experience of interoceptive sensations than nonmeditators.

I considered that critical support for Hypothesis #1 could be derived from the following evidence: (1) increased group heartbeat detection accuracy rates and increased numbers of good heartbeat detectors in the meditators, (2) increased awareness of heartbeat and breathing sensations in meditators at lower doses of isoproterenol, (3) greater accuracy in tracking the ongoing ebb and flow of interoceptive sensations at levels that are consciously perceived by the majority of individuals. I assumed that any

such evidence in support of Hypothesis #1 would not be undermined by differences in level of peripheral arousal between the groups, such as a differential heart rate response in the meditators. Given the limitations associated with the heartbeat detection study (Chapter 4), I placed a greater emphasis on the possibility of obtaining support for Hypothesis #1 from the isoproterenol study (Chapter 6). On the other hand, I considered that the absence of a finding with the isoproterenol method would constitute grounds for falsification of Hypothesis #1.

The second hypothesis is that the long term practice of meditation is associated with an enhanced ability to regulate body states occurring in the context of acute physiological arousal. This hypothesis is derived from an extensive literature associating reductions in physiological arousal with the acute and chronic meditation practice, as well as a serendipitous finding reported in a recent case study that meditation was capable of lowering pharmacologically induced arousal.

To test Hypothesis #2, I assessed the impact of the meditation practice on the cardiovascular response to isoproterenol (Chapter 7). I predicted that, in the face of isoproterenol infusions, during the meditation practice meditators would display lower heart rate increases than nonmeditators during a relaxation practice. I further predicted that such heart rate reductions in the meditators would be specific to meditation, i.e., that meditators and nonmeditators would have equivalent heart rate responses to isoproterenol at rest.

I considered that critical support for Hypothesis #2 could be derived from the following evidence: (1) at moderate doses of isoproterenol, observing greater heart rate reductions in meditators during the meditation practice as compared to nonmeditators

during a relaxation practice (2) at moderate doses of isoproterenol, observing heart rate reductions in even a single meditator during meditation. I considered that the absence of such a finding at the group or individual level would constitute grounds for falsification of Hypothesis #2.

CHAPTER 4. INTEROCEPTIVE AWARENESS IN EXPERIENCED MEDITATORS[1]

4.1 Background

Several methods for assessing interoceptive awareness have been described, including gastrointestinal distension (Holzl et al., 1996), adrenergic stimulation (Cameron and Minoshima, 2002; Khalsa et al., In press), and heartbeat perception (Brener and Kluvitse, 1988 ; Schandry, 1981; Whitehead et al., 1977). Heartbeat perception has traditionally been the most commonly utilized method, primarily due to the phenomenological relevance of heartbeat sensations to the experience of emotion (Wiens et al., 2000), as well as the technical and non-invasive ease with which this signal can be measured (Jones, 1994; Phillips et al., 1999). Factors modulating awareness of cardiac sensations during the performance of heartbeat perception tasks have been extensively described, including the effects of body mass index (Rouse et al., 1988), body position (Jones et al., 1987), physical (Barsky et al., 1998; Herbert et al., 2007; Schandry et al., 1993) and mental exertion (Eichler and Katkin, 1994), and judgments of temporal simultaneity and mechanical sensitivity (Brener et al., 1993; Knapp et al., 1997; Ring and Brener, 1992) (for a comprehensive overview see (Jones, 1994)). Recently, functional neuroimaging studies have demonstrated that heartbeat perception tasks activate a network of brain regions including the insula, primary somatosensory cortex and the anterior cingulate cortex (Craig, 2002; Critchley et al., 2004; Pollatos et al., 2007c). These brain regions are considered necessary for the representation and maintenance of the internal state of the organism (Craig, 2002; Critchley et al., 2004; Pollatos et al., 2007c) and for the conscious experience of emotion and feelings (Damasio et al., 2000).

[1] A modified version of this chapter has been accepted for publication (see Khalsa et al, in press).

Although there are several techniques for assessing heartbeat perception, the most commonly used methods are heartbeat detection and heartbeat tracking. During heartbeat detection, subjects determine whether an exteroceptive stimulus, such as a light or a tone, is contemporaneous with their heartbeat sensation (Brener and Kluvitse, 1988; Schneider et al., 1998; Whitehead et al., 1977). Performance is indexed by the number of correct responses reported by the subject (e.g., true positives and true negatives), which also allows measurement of individual and group response accuracy. Subjects are then classified as 'good heartbeat detectors' when their performance lies above chance according to the binomial distribution (Katkin et al., 2001; Schneider et al., 1998; Wiens and Palmer, 2001). During heartbeat tracking, subjects silently count their heartbeats during brief, fixed time periods. Performance is indexed by a cardiac perception score, in which the number of counted heartbeats is contrasted with the number of actual heartbeats. Subjects are classified as 'good heartbeat perceivers' when their scores fall above a predetermined level (Herbert et al., 2007). Heartbeat detection has been the more commonly utilized measure, perhaps because it appears to suffer from less methodological confounds than heartbeat tracking. Such confounds include the lack of a statistical measure to evaluate individual performance, the possible influence of a priori knowledge about average heart rate on the rate of counting (Phillips et al., 1999; Ring and Brener, 1996), and the insensitivity of heartbeat tracking tasks to changes in heart rate (Windmann et al., 1999). Consequently, I selected heartbeat detection as an index of interoceptive awareness.

I identified experienced meditators from two different meditation traditions that are extensively practiced within the United States: Tibetan Buddhism and Kundalini

yoga. I selected these traditions to examine whether the effects of the meditation practice on interoceptive awareness were consistent across traditions, despite the fact that each tradition adopts slightly differing approaches to the cultivation of interoceptive awareness. For example, in Tibetan Buddhism interoceptive awareness is more commonly cultivated while meditating under resting physiological conditions, whereas in Kundalini yoga interoceptive awareness is more commonly cultivated during yoga exercises that elicit conditions of mild physiological arousal.

I hypothesized that the long term practice of meditation leads to enhanced interoceptive awareness. On this basis, I predicted that experienced meditators from both traditions would display enhanced awareness of heartbeat sensations during performance of a heartbeat detection task at rest. I further hypothesized that experienced meditators would display metacognitive awareness of this enhancement, that is, knowledge of accurate self performance, based on the rationale that meditation cultivates a monitoring of experience at levels beyond mere interoceptive processing. I predicted that metacognitive awareness would be reflected through more accurate subjective ratings of interoceptive task performance in both groups of meditators than in non-meditators.

4.2 Method

4.2.1 Participants

Seventeen non-meditators, 17 Kundalini meditators, and 13 Tibetan Buddhist meditators participated in the study (**Table 1**). Meditators were selected according to three criteria: 1) a minimum of 15 years of formal meditation practice, 2) a self reported strong daily practice, and 3) having attended at least one meditation retreat during the

previous year. Non-meditators were identified as individuals who had never attended a formal yoga or meditation course and did not practice self-taught meditation. All groups were matched with respect to age and body mass index. Any subject reporting a history of neurological or psychiatric disease was excluded from the study. Based on this criterion, one Kundalini meditator and two non-meditators were precluded from study participation.

4.2.2 Tasks

Subjects performed two types of tasks: a pulse detection familiarization task and a heartbeat detection task. Each task utilized identical stimuli but required a different attentional focus. During pulse detection, subjects took their non-dominant wrist pulse and were required to judge whether a train of exteroceptive stimuli (800 Hz, 50 ms tones) were simultaneous or non-simultaneous with pulse sensations. During heartbeat detection subjects were not allowed to take their pulse and were required to judge whether the tones were simultaneous or non-simultaneous with perceived heartbeat sensations (**Figure 3**).

Tone delivery was triggered by each myocardial contraction, as measured (indirectly) from the R-wave of a lead II electrocardiogram (MP100 acquisition unit, Biopac Systems, Inc.). During simultaneous trials, tones were delivered at the same time as the subject's own finger pulse, approximately 250-300 ms after the R-wave[2] (corresponding to the R-wave to pulse interval, or RPI). The finger pulse was measured with an infrared photoplethysmograph (TSD123B) attached to the distal phalange of the fifth digit of the dominant hand. The RPI was measured for each subject by calculating

[2] This delay, around 250 to 300 ms, has been shown to lead to the perception by accurate heartbeat detectors that heartbeats and tones are "simultaneous" (Rouse et al, 1988; Ring et al, 1992; Brener et al, 1993; Schandry et al, 1993; Jones, 1994; Eichler et al, 1994, Knapp et al, 1997).

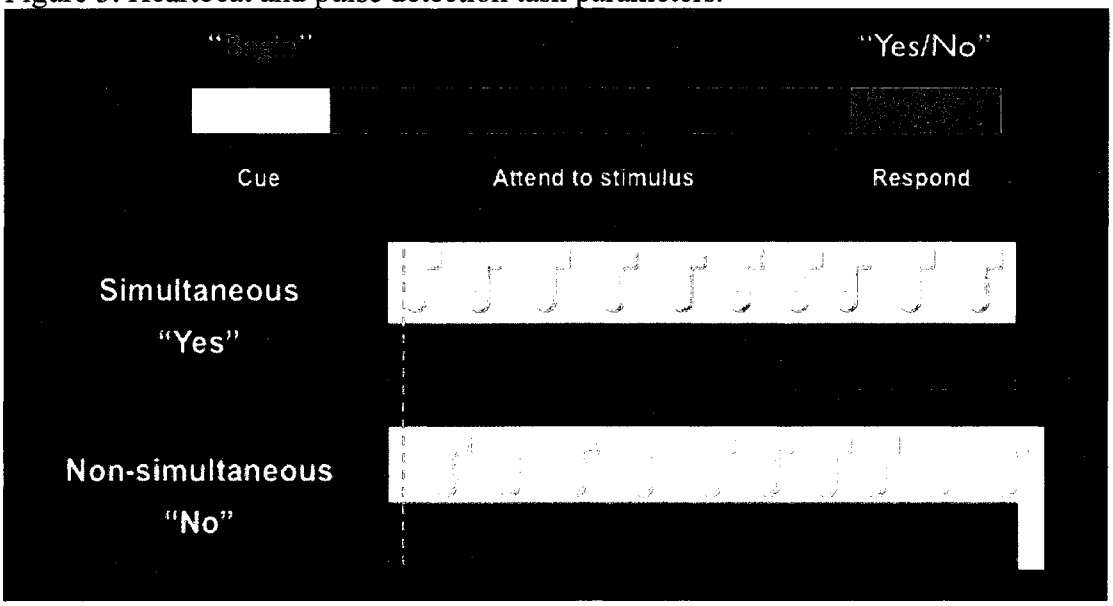
the average delay between the peak of the R-wave and the foot of the systolic upstroke measured during a two minute resting period. Mean resting heart rate and RPI intervals are listed in **Table 2**.[3] During nonsimultaneous trials, tones were delivered 400 ms after the RPI, approximately 650-700 ms after the R-wave. Thus tone delivery was temporally linked to each subject's actual heartbeat during each trial. Trial order was randomized within and across each block. Tones were presented through noise canceling headphones (QuietComfort, Bose Inc., Framingham, MA). All participants performed the tasks in the supine position with their eyes closed, and they were given an unlimited time to respond during each trial.

4.2.3 Procedure

The study involved two visits, spaced 1-14 days apart. At the beginning of each visit resting pulse and heart rate were measured for two minutes. After each resting period, the pulse plethysmograph was removed in order to prevent subjects from deriving heartbeat information from the finger pulse sensation during the subsequent tasks. During the first visit participants performed one block of pulse detection followed by two blocks of heartbeat detection, in the same order. During the second visit participants repeated both blocks of heartbeat detection, in the same order as before. All blocks consisted of 23 trials. Any subject not meeting the criterion for good pulse detection ($\geq$ 16 out of 23 trials correct, $p < .05$ per binomial test) during the first visit was excused from the study (one non-meditator was excluded based on this criteria). During the first heartbeat detection block (HB1), subjects were instructed to breathe normally. During the second heartbeat detection block (HB2), subjects were instructed to practice a yogic breathing pattern:

[3] These intervals are similar to those observed when measuring the RPI from the finger pulse (Teng & Zhang, 2006). However, shorter intervals have been reported when measuring the RPI from the ear pulse, possibly due to the shorter distance traveled by the pulse wave (de Boer et al, 2007a; 2007b).

Figure 3. Heartbeat and pulse detection task parameters.



Note: Each trial consisted of an auditory cue period (e.g. 'begin'), a variable period of attending to the stimulus, followed by a response period (e.g. 'yes'/'no'). On 50% of the trials the tones were presented simultaneously with heartbeat or pulse sensations; on the other 50% of the trials the tones were presented non-simultaneously with heartbeat or pulse sensations.

Ujjai breath, a technique that involves symmetric long deep nostril breathing against airway resistance (Brown and Gerbarg, 2005). Respiratory rate was measured during all tasks with a thoracic respiratory belt (RSP100C). Each subject's respiratory patterns were examined for compliance with the Ujjai breathing condition after completion of the task. All subjects demonstrated satisfactory respiratory patterns indicating accurate performance of the Ujjai breath. Aside from this breathing technique, no formal meditation instruction was given to the participants. I controlled for breathing patterns during heart beat detection for two related reasons: (1) spontaneous respiratory manipulations have been observed to occur in subjects in the absence of an instruction to breathe normally, and have been suggested as a potential strategy for maximizing heartbeat sensations (Jones, 1994; Weisz et al., 1988), and (2) several meditators were

observed to spontaneously display Ujjai breathing during the piloting phase of the study and this, in and of itself, could be a basis for enhanced interoceptive accuracy. One Kundalini meditator was unable to perform the Ujjai breathing due to a preexisting respiratory condition and was excluded from the heartbeat detection analysis.

4.2.4 Subjective ratings

Prior to performing each task, participants were asked to predict task accuracy (e.g., "How good do you think you will be at [task X]?") and difficulty ("How hard do you think [task X] will be?"). Upon completion of each task participants were also asked to estimate task accuracy ("How good do you think you were at [task X]?") and difficulty ("How hard do you think [task X] was?"). Accuracy ratings could range from 1 ("very bad") to 5 ("very good"). Difficulty ratings could range from 1 ("very hard") to 5 ("very easy"). To familiarize participants with each task, all participants were instructed to sample tones from each trial type (i.e., one simultaneous and one non-simultaneous trial) for an unlimited period prior to performing each task. In addition, task related feedback was withheld from all participants until the conclusion of the study.

4.2.5 Accuracy measures

Accuracy scores were calculated using A' = [1/2+((HR-FP)(1+HR-FP))/(4HR(1-FP))], a non-parametric signal detection analog of d' ideal for signal detection conditions with low trial numbers (Grier, 1971). In this formula, HR = Hit Rate and FP = False positive. Following methods commonly utilized in heartbeat detection studies (Brener et al., 1993; Jones et al., 1984; Rouse et al., 1988), A' scores were normalized using the following formula: 2arcsin(sqrt (A')), such that performance ranged from 0 to π (chance = $\pi/2$). Subjects were further classified as "good heartbeat detectors" if they displayed

above chance performance during a block of testing, defined as $\geq$ 16 out of 23 trials correct, $p < .05$ per binomial test, following the approach of previous studies (Katkin et al., 2001; Schneider et al., 1998; Wiens and Palmer, 2001). Since no differences were predicted between the two groups of meditators, the overall analyses examined the three groups separately. All univariate repeated measures ANOVA tests were assessed for violations of the sphericity assumption, and when violated, were corrected with the Huynh-Feldt method. In these instances the corrected p values are reported, along with the Huynh-Feldt epsilon (ε) correction.

4.3 Results

4.3.1 Participants

Both groups of meditators reported significantly more years of meditation practice $F(2,44) = 120.5$, $p < .001$, and hours of cumulative meditation practice, $F(2,44) = 31.9$, $p < .001$, than the non-meditators. The groups did not differ with respect to age $F(2, 44) = .45$, $p = .64$, or BMI $F(2, 44) = 1.07$, $p = .35$, (**Table 1**). There were also no differences between the proportion of males and females in the non-meditators and the Kundalini meditators $\chi_1 = .15$, $p = .70$, or the Tibetan Buddhist meditators $\chi_1 = 1.76$, $p = .19$.

4.3.2 Cardiovascular parameters

A 3x2 repeated measures ANOVA did not reveal any group differences in resting heart rate $F(2, 44) = .42$, $p = .66$, $\eta_p^2 = .02$. There was no effect of visit on resting heart rate $F(1, 44) = 2.18$, $p = .15$, $\eta_p^2 = .05$, and there were no group by visit interactions $F(2, 44) = .86$, $p = .43$ $\eta_p^2 = .04$. The groups also did not differ with respect to the R-wave to pulse interval $F(2, 44) = 1.34$, $p = .26$, $\eta_p^2 = .06$. There was no effect of visit on the R-

wave to pulse interval $F(1, 44) = .10$, $p = .75$, $\eta_p^2 = .002$, and there were no group by visit interactions $F(2, 44) = .38$, $p = .69$ $\eta_p^2 = .02$.

Table 1. Heartbeat detection group demographic data.

	Non-meditators (NM)	Kundalini (KM)	Tibetan Buddhist (TB)
Sex	4M:13F	5M:12F	7M:6F
Age (yrs)	50.6 +/- 9.6	52.1 +/- 8.6	48.8 +/- 10.1
Body Mass Index	24.8 +/- 5.1	24.0 +/- 5.2	22.3 +/- 3.3
Meditation practice (yrs)	0 +/- 0	29.3 +/- 6.4	24.7 +/- 8.4
Cumulative meditation practice (hrs)	0 +/- 0	17660 +/- 9128	24903 +/- 14270

Means +/- standard deviation.

Table 2. Heartbeat detection cardiovascular parameters.

	Non-meditators (NM)	Kundalini (KM)	Tibetan Buddhist (TB)
Resting heart rate – visit 1 (bpm)	63.3 +/- 10.0	67.0 +/- 8.7	65.6 +/- 14.9
Resting heart rate – visit 2 (bpm)	65.8 +/- 8.4	68.8 +/- 11.5	65.3 +/- 15.3
R-wave to pulse interval - visit 1 (s)	.269 +/- .017	.261 +/- .013	.266 +/- .016
R-wave to pulse interval - visit 2 (s)	.266 +/- .015	.260 +/- .014	.264 +/- .014

Means +/- standard deviation.

4.3.3 Accuracy measures

There were no group differences in accuracy on the pulse detection task $F(2,44) = 1.27$, $p = .29$. A 3x2x2 ANOVA was ran on heartbeat detection accuracy with group (Kundalini, Tibetan Buddhist, controls) as the between subjects factor and with block (block 1 and block 2) and visit (visit 1 and visit 2) as within subjects factors. There were no main effects for group $F(2, 43) = .30$, $p = .74$, $\eta_p^2 = .01$, block, $F(1, 43) = .69$, $p = .41$, $\eta_p^2 = .02$, or visit, $F(1, 43) = 1.38$, $p = .25$, $\eta_p^2 = .03$, and there were no significant interactions between group and visit, $F(2, 43) = .77$, $p = .47$, $\eta_p^2 = .04$, block and visit,

$F(1, 43) = .000$, $p = .99$, $\eta_p^2 = .00$ or group and block and visit, $F(2, 43) = 1.03$, $p = .37$, $\eta_p^2 = .05$ (**Figure 4**). The lack of group differences was not accounted for by group differences in response bias, defined as the tendency to favor one particular response type over another, for either pulse detection $F(2,44) = .1$, $p = .91$, or heartbeat detection $F(2, 43) = 1.3$, $p = .28$, $\eta_p^2 = .06$.

There were also no differences in the proportion of meditators versus nonmeditators classified as good heartbeat detectors (**Table 3**). This was equally true when the definition of good heartbeat detection performance was restricted to above chance performance on 2 out of 2 visits, or loosened to above chance performance on at least 1 out of 2 visits, for both tasks (**Table 3**).

4.3.4 Subjective ratings

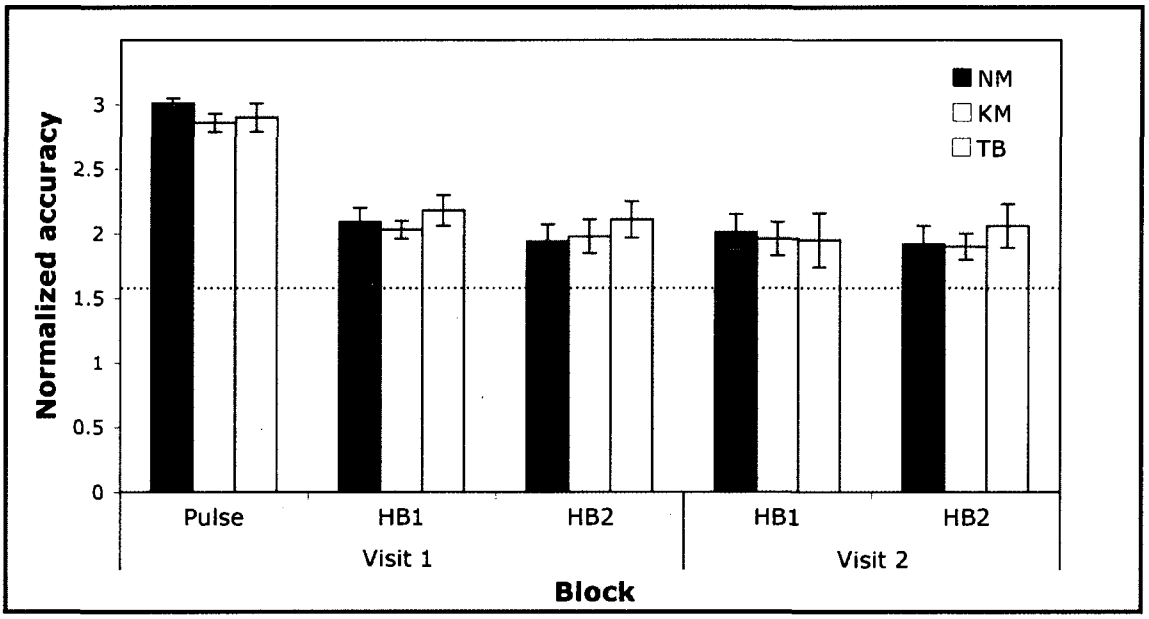
There were no group differences in the ratings of pulse detection accuracy $F(2, 44) = .12$, $p = .89$, $\eta_p^2 = .01$ or pulse detection difficulty $F(2, 44) = .76$, $p = .48$, $\eta_p^2 = .03$. However, a 3x2x2 ANOVA with two repeated measures factors revealed significant group differences in ratings of heartbeat detection accuracy $F(2,43) = 5.77$, $p = .007$, $\eta_p^2 = .21$, and heartbeat detection difficulty $F(2, 43) = 4.1$, $p = .023$, $\eta_p^2 = .16$, with both groups of meditators rating their heartbeat detection performance to be more accurate and the task to be less difficult than the non-meditators (**Figures 5 & 6**). There were no other significant main effects or interactions for ratings of heartbeat detection accuracy. For ratings of heartbeat detection difficulty, there was a significant effect of visit $F(2,1) = 4.5$, $p = .039$, $\eta_p^2 = .1$, with all groups rating both tasks as less difficult on the second visit. There was a significant interaction between group and block, $F(2, 2) = 4.7$, $p = .015$, $\eta_p^2 = .18$, with both groups of meditators rating each block to be less difficult than the non-

meditators. There was also a significant interaction between block and visit $F(2,1) = 4.3$, $p = .045$, $\eta_p^2 = .1$, with all groups rating blocks from the second visit to be easier than the first visit.

4.3.5 Post analysis

Both groups of meditators displayed higher subjective ratings of heartbeat detection accuracy and lower subjective ratings of heartbeat detection difficulty than non-meditators. Because these findings occurred in the absence of an actual difference in heartbeat detection accuracy, I examined the relationship between the objective accuracy scores and the subjective accuracy ratings provided by each participant after the pulse and heartbeat detection tasks. Since maximum objective accuracy was almost always reached for pulse detection, I assumed that the subjective accuracy ratings for pulse detection represented the maximum possible range for subjective accuracy ratings in general. I then normalized each participant's subjective heartbeat detection rating by the global average subjective pulse detection accuracy ratings measured from all participants using the following formula: (individual heartbeat detection accuracy rating – global mean pulse detection accuracy rating)/global mean pulse detection accuracy rating. I also normalized each group's heartbeat detection accuracy scores (A') by the mean pulse detection accuracy scores using this same procedure. Finally, I examined the relationship between these normalized heartbeat detection ratings and normalized accuracy scores for each group for congruency. I found that on average, meditators' subjective accuracy ratings appeared more congruent with objective accuracy scores than the non-meditators (**Table 4**). There was a nearly significant interaction between group and scale, $F(2,2) = 2.6$, $p = .08$, $\eta_p^2 = .1$, in support of this dissociation.

Figure 4. Heartbeat and pulse detection accuracy.



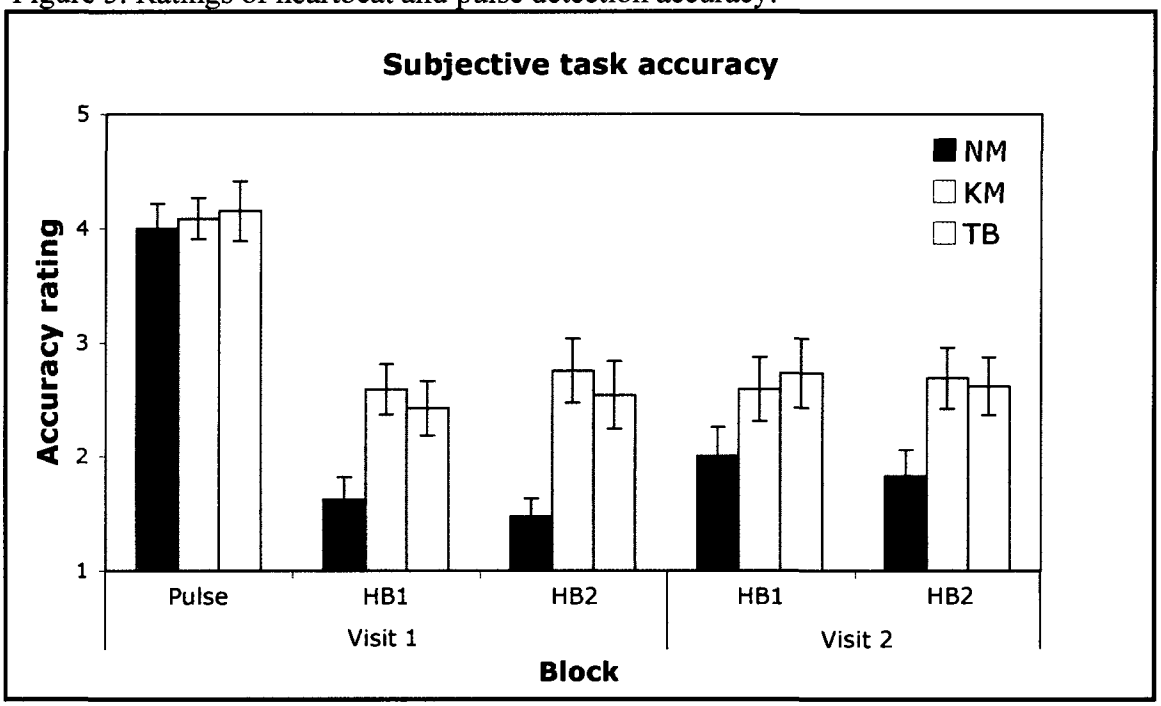
HB1: heartbeat detection during normal breathing. HB2: heartbeat detection during Ujjai breathing. NM: non-meditators. KM: Kundalini meditators. TB: Tibetan Buddhist meditators. Performance accuracy could range from 0 to π, with chance performance = $\pi/2$. Dotted line = chance. Means +/- SE.

Table 3. Frequency of good heartbeat detectors.

	Good heartbeat detectors - HB1			Good heartbeat detectors - HB2		
# of visits above chance	0/2	1/2	2/2	0/2	1/2	2/2
NM (n=17)	47% (8)	18% (3)	35% (6)	47% (8)	18% (3)	35% (6)
KM (n=17)	35% (6)	47% (8)	17% (3)	38% (6)	50% (8)	13% (2)
$\chi^2_1 \geq$ 1/2 visits		χ^2_1=.49, p=.24			χ^2_1=.31, p=.29	
χ^2_1 2/2 visits			χ^2_1=0, p=.49			χ_1=.14, p=.35
TB (n=13)	46% (6)	23% (3)	31% (4)	31% (4)	38% (5)	31% (4)
$\chi^2_1 \geq$ 1/2 visits		χ_1=.002,p=.48			χ_1=.28,p=.30	
χ^2_1 2/2 visits			χ_1=.02,p=.44			χ_1=.11,p=.37

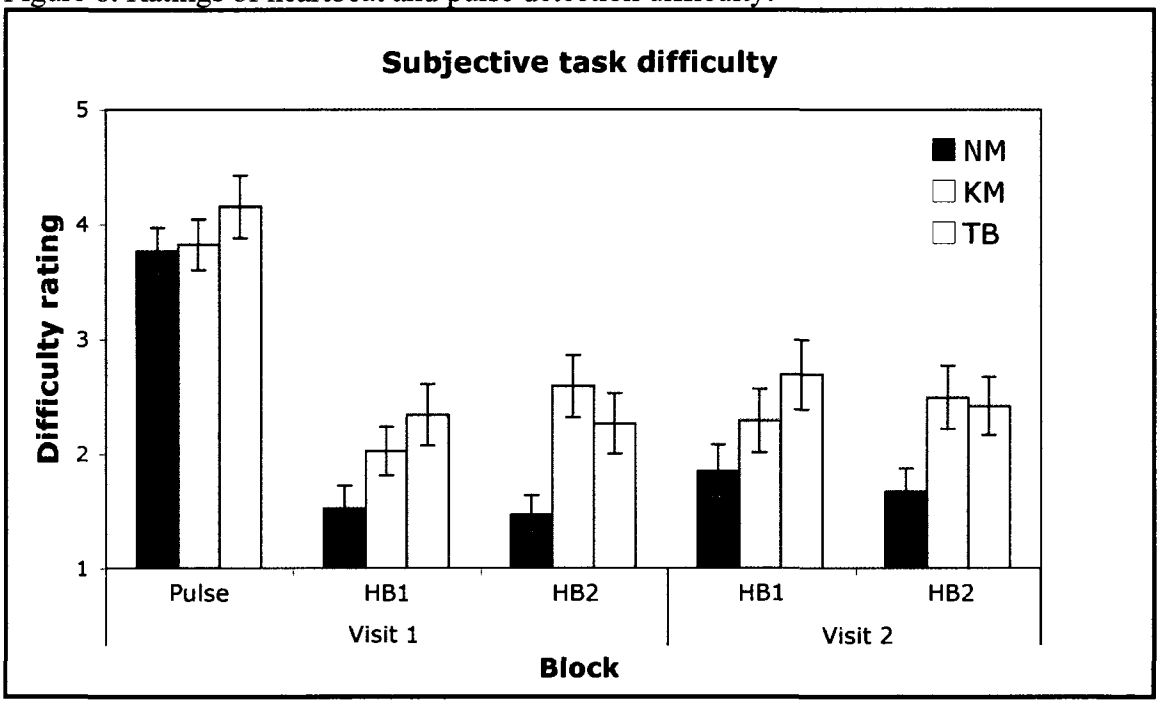
Note: The numbers of individuals meeting each criterion are listed in parentheses. A Chi-square with one degree of freedom compares whether the proportion of meditators classified as good heartbeat detectors differs from the non-meditators. NM: non-meditators. KM: Kundalini meditators. TB: Tibetan Buddhist meditators. Only 16 Kundalini meditators completed testing in block 2.

Figure 5. Ratings of heartbeat and pulse detection accuracy.



Accuracy ratings could range from 1 ("very bad") to 5 ("very good"). NM: non-meditators. KM: Kundalini meditators. TB: Tibetan Buddhist meditators. Means +/- SE.

Figure 6. Ratings of heartbeat and pulse detection difficulty.



Difficulty ratings could range from 1 ("very hard") to 5 ("very easy"). NM: non-meditators. KM: Kundalini meditators. TB: Tibetan Buddhist meditators. Means +/- SE..

Table 4. Normalized objective and subjective heartbeat detection accuracy.

	Nonmeditators	Kundalini	Tibetan Buddhist
Normalized objective heartbeat detection accuracy	0.45 (.10)	0.40 (.10)	0.46 (.14)
Normalized subjective heartbeat detection accuracy	0.27 (.08)	0.51 (.09)	0.51 (.10)

Means (SE), range 0-1.

4.4 Discussion

The current findings do not support the hypothesis that experienced meditators would display increased interoceptive awareness, as meditators did not differ from non-meditators in heartbeat detection accuracy. The lack of an effect of meditation on awareness of heartbeat sensations appears to be a reliable finding. It occurs in two different groups of experienced meditators, measured at two time points, and with two different respiratory manipulation strategies. These results are consistent with recent findings by Nielsen and Kaszniak (2006), who reported a lack of significant differences between a group of Buddhist meditators and a group of non-meditators on a single session of standard heartbeat detection. The Nielsen and Kaszniak (2006) study had a small sample size, did not include comparison subjects matched for age or body mass (Rouse et al., 1988), and was conducted in a small number of sessions, limiting statistical power. The present study, however, did not suffer from any of these limitations, and still did not reveal any effect of meditation on interoceptive awareness. I conducted a power analysis based on the observed main effect to determine the sample size required to achieve a statistically meaningful result for heartbeat detection. I found that group sizes would need to be increased by one order of magnitude before reaching the threshold of significance. Thus if the sample sizes were increased tenfold, the estimated main effect would be as follows: $F(2, 457) = 3.21$, $p = .041$, $\eta_p^2 = .01$. Even if this were the case, the

presumed effect size suggests that the influence of meditative experience on resting awareness of heartbeat sensations would be quite small.

Although I believe that the current finding is reliable, it is important to consider alternatives that might explain it. First, it is possible that awareness of heartbeat sensations alone is a poor index of the type of interoceptive sensations cultivated by the practice of meditation. Although attention to body sensations such as the heartbeat is practiced at some point of the training in all meditation traditions, attention is more commonly directed toward breathing. Any enhancement of interoceptive sensations that results from the long term practice of meditation might be specific only to the bodily signals which are attended. Thus the current results do not rule out the possibility that meditation cultivates interoceptive awareness for other body signals such as breathing. Second, attention to non-bodily signals is also frequently practiced in all meditation traditions. For example, in the Tibetan Buddhist tradition, attention is commonly focused on complex mental imagery or external visual objects during meditation (Lutz, 2007), and the awareness that develops during such attention training might not translate readily into an enhancement of interoceptive awareness. Third, the current study only examined interoceptive awareness under resting conditions. I chose this starting point because the meditation practice most commonly occurs during those conditions. It is possible that interoceptive awareness for heart beat sensations is limited at rest by a physiological mechanism not amenable to voluntary modulation, even through a long standing meditation practice. Of note, none of the groups in the current study displayed heartbeat detection rates above 50 percent. These rates are consistent with those routinely reported in the heartbeat detection literature, in which the frequency of good detectors are rarely

higher than 40 percent. (Brener and Kluvitse, 1988; Eichler and Katkin, 1994; Jones, 1994; Knapp et al., 1997; Ring and Brener, 1992; Wiens and Palmer, 2001), suggesting that it is difficult for most individuals to display awareness of heartbeat sensations at rest. However, the current finding does not guarantee that meditation would not be associated with enhanced interoceptive awareness under other physiological conditions. Indeed, visceral sensations do not dominate conscious experience under resting conditions, but quickly develop when conditions such as exercise or stress signal deviations in the homeostatic state (Cameron and Minoshima, 2002; Khalsa et al., In press). Thus it is still possible that meditators would display increased interoceptive awareness under these conditions. Such considerations argue for the development of new measures of interoceptive awareness that take into account non-homeostatic physiological body states.

Both groups of meditators displayed higher subjective ratings of heartbeat detection accuracy and lower subjective ratings of heartbeat detection difficulty than non-meditators. In the absence of an actual difference in heartbeat detection accuracy these findings were surprising. The ratings differences did not appear to be due to a general rating bias, as there were no such group differences in the ratings of the pulse detection task. All groups displayed accurate pulse detection performance, rated their accuracy accordingly, and found the task to be easy. With respect to heartbeat detection, the non-meditators' ratings were near the bottom of each scale, suggesting that they found the task to be difficult and felt that their performance was very poor. The meditators' ratings were near the middle of the scale, suggesting that they found the task to be neither easy nor difficult, and felt that their performance was neither good nor bad. These rating differences could be explained either by the non-meditators underestimating their

performance, or the meditators overestimating their performance. Even though both groups displayed performance within the normally reported range on the heartbeat detection task, 'normal' performance is quite often below chance given the fact that heartbeat detection is most commonly measured at rest. Thus it could be argued that either the meditators' or the non-meditators' ratings were congruent with the literature. An analysis of the relationship between each group's objective accuracy scores and subjective ratings of accuracy suggests it is more likely that the non-meditators were underestimating their heartbeat detection performance, and provides support, albeit limited, for the notion that experienced meditators' subjective perceptions of interoceptive states are more in tune with their performance on interoceptive tasks.

Overall, the results of this study provides evidence against the notion that practicing attention to internal body sensations, a core feature of meditation, enhances resting interoceptive awareness. However, this conclusion is limited by the fact that only a minority of participants demonstrated awareness of heartbeat sensations. Therefore, additional evidence is needed before the hypothesis can be supported or falsified. Since all neurologically intact individuals have had an experience of heartbeat sensations as a part of daily life, it is imperative to develop measures capable of demonstrating this type of interoceptive awareness in all or most of the participants. Furthermore, since meditators more commonly cultivate awareness of breathing sensations it is important to also develop measures capable of demonstrating awareness of these sensations.

CHAPTER 5. A NOVEL METHOD FOR ASSESSING INTEROCEPTIVE AWARENESS[4]

5.1 Background

Although heartbeat detection has been highly utilized as a measure of interoceptive awareness, the fact that most individuals display chance performance when assessed via heartbeat detection tasks has remained a curious and scientifically frustrating fact. Such low rates of detection were observed in the previous study, and similarly low rates have been documented since the inception of methodology for assessing heartbeat detection, regardless of the utilized heartbeat detection method, sample size, participant characteristics or research question (Brener & Kluvitse, 1988; Brener, Liu, & Ring, 1993; Eichler & Katkin, 1994; Jones, Jones, Rouse, Scott, & Caldwell, 1987; Jones, O'Leary, & Pipkin, 1984; Knapp, Ring, & Brener, 1997; Knapp-Kline & Kline, 2005; Ring & Brener, 1992; Rouse, Jones, & Jones, 1988; Schneider, Ring, & Katkin, 1998; Whitehead, Drescher, & Heiman, 1977; Wiens & Palmer, 2001; Yates, Jones, Marie, & Hogben, 1985; Khalsa et al, in press). Furthermore, it has been noted that participants frequently report they were simply guessing during the heartbeat detection task (Wiens, 2005). Low rates of awareness are also congruent with results from heartbeat tracking tasks, where it is common for investigators to have to screen and exclude a much larger number of "poor perceivers" in order to obtain equal numbers of good and poor perceivers (Pollatos et al., 2007b; Pollatos et al., 2005). A clue as to why this may be comes from the fact that most studies of heartbeat perception occur under conditions of physiological rest, when there are few deviations from the baseline state of the body. Indeed, heartbeat perception accuracy has been reported to increase when deviations from baseline body states occur

[4] A modified version of this chapter has been accepted for publication (see Khalsa et al, in press).

such as during exercise or stress (Jones and Hollandsworth, 1981; Schandry et al., 1993). This suggests that there is an inherent limitation in the ability to detect the heartbeat at rest, and that this limitation may be overcome during conditions of increased physiological arousal. If the role of interoceptive sensation in the experience of meditation is to be clarified, additional approaches must be developed that can reliably manipulate and measure interoceptive awareness in most—ideally, perhaps even all—participants.

Adrenergic stimulation represents one promising solution to the limitations imposed by conducting heartbeat perception tasks at rest. This approach provides the ability to reversibly modulate the bodily state of the organism above baseline levels, in a sympathomimetic manner that also resembles a subset of the physiological changes known to occur during emotional states. Consequently, it comes as no surprise that adrenergic stimulants have been utilized in influential emotion research during the past century (Marañon, 1924; Reisenzein, 1983; Schacter, 1962). However, despite the promiment impact of this approach no standard protocols exist for assessing subjective awareness of the interoceptive states produced by these agents. Thus although Maranon (1924) and Schacter & Singer (1962) manipulated the state of the body using epinephrine injections, both relied on open ended descriptions and a basic retrospective assessment of the interoceptive sensations induced by these infusions. Furthermore, because Schacter & Singer (1962) and others (Marshall, 1979; Mezzacappa, 1999) have relied on subcutaneous injections of epinephrine, the time course during which changes in body state were elicited varied between 10 minutes to an hour. Given the transient nature of many emotional states (Ben-Ze'ev, 2000; Davidson, 2003; Hutcherson et al., 2005) and

the interoceptive sensations associated with them, alternative techniques for inducing similar changes in interoceptive awareness are needed.

One promising protocol that has emerged consists of a standardized isoproterenol sensitivity test. This involves the graded administration of isoproterenol, a non selective beta adrenergic agonist (Arnold and McDevitt, 1983; Cleaveland et al., 1972; Contrada et al., 1991; George et al., 1972; Martinsson et al., 1989; Mills et al., 1998; Yu et al., 2007). When administered intravenously, isoproterenol primarily results in rapid elevations in heart rate and contractility, relaxation of bronchial smooth muscle, and reductions in diastolic blood pressure. The pharmacological effects of isoproterenol are transient, owing to a short half-life in the blood (Conolly et al., 1972), providing an opportunity for repeated administrations with reproducible effects within a single experimental session (Martinsson et al., 1989). Furthermore, since isoproterenol is believed to only minimally cross the blood brain barrier (Borges et al., 1999; Murphy and Johanson, 1985; Olesen et al., 1978), it is unlikely that the effects of isoproterenol administration result directly in changes in brain activity. This presents a unique opportunity to examine the effects of stimulation restricted to afferent sensory nerve fibers on interoceptive awareness and emotional experience.

Although it has been known for some time that the pharmacological effects of isoproterenol elicit changes in cardiac and respiratory sensations (Cleaveland et al., 1972; George et al., 1972), only one study has examined the neural basis of these changes. In a recent Positron Emission Tomography study, Cameron and Minoshima (2002) administered a continuous infusion of either isoproterenol to maintain a heart rate of 120 beats per minute (bpm) in one group, or a saline placebo infusion for 30 minutes in

another group. Using a single blinded design, participants were asked to rate their awareness of cardiac, respiratory, and affective symptoms, before and after completion of the infusion period. In both groups isoproterenol or saline administration was preceded by infusion of a fluorodeoxyglucose radiotracer in order to assess isoproterenol induced changes in regional cerebral glucose metabolism. Participants in the isoproterenol but not the saline infusion condition reported an increase in awareness of cardiac and respiratory sensations, as well as an increase in symptoms of physical anxiety, mental anxiety and distress. These changes in interoceptive sensations were concomitant with regional increases in glucose metabolism in brain regions including the right insula, left SI, and dorsal cingulate cortex. This enhancement of metabolism in interoceptive brain regions further illustrates the validity of isoproterenol as a tool for measuring interoceptive awareness, and the reported changes in affective state also emphasize its relevance for emotion research.

In the Cameron & Minoshima (2002) paradigm, isoproterenol was titrated to maintain a constant and elevated level of body arousal. However, since perceived body states during the experience of emotion and other daily events are not static, a more desirable approach involves assessing interoceptive awareness produced by various levels of transient bodily changes, as are found in standard isoproterenol sensitivity tests. Furthermore, since the practice of meditation cultivates an ongoing, moment-to-moment awareness of interoceptive states, creating a paradigm capable of inducing similar momentary changes in perceived body state would be highly useful.

In response to the limitations of conventional interoceptive awareness tasks described above, and based on the promise of the isoproterenol approach, I developed a

novel protocol for manipulating and measuring interoceptive awareness. This protocol was based on the standardized isoproterenol sensitivity test, and involved multiple bolus administrations of isoproterenol in a randomized, double blinded, and placebo controlled manner.

In order to elicit a full range of changes in interoceptive awareness, I chose doses that were likely to be below and above thresholds for detection in each participant, based on preliminary testing. As a first pass measure of these changes in interoceptive awareness, I employed retrospective ratings of interoceptive sensations in a manner similar to (Cameron and Minoshima, 2002). I supplemented these retrospective ratings with continuous dial ratings of the intensity of interoceptive sensations experienced throughout each infusion, a form of continual self monitoring that helps minimize demand characteristics, response biases and potential memory confounds associated with retrospective ratings (Craske, 1999; Hutcherson et al., 2005). Finally, since there may be confounds associated with asking participants to explicitly rate the experience of subconscious stimuli (Cleeremans, 1998), I employed a post infusion wagering task that required participants to place imaginary wagers on whether they had received isoproterenol or saline (placebo). This measure was based on post decision wagering, a newly developed measure purported to be an intuitive and direct measure of awareness (Persaud et al., 2007).

I hypothesized that bolus infusions of isoproterenol would result in dose-dependent increases in retrospective ratings of heartbeat and breathing sensations, as indexed by intensity ratings of heartbeat and breathing sensations and post infusion wagering. I also hypothesized that there would be a dose-dependent correlation between

the continuous subjective ratings of isoproterenol-related interoceptive sensations and the objective bodily response to isoproterenol, as indexed by the change in heart rate. Critically, I determined whether the aforementioned changes in interoceptive awareness would be detectable in the majority of participants, at least at higher doses, which would overcome a major limitation of extant heartbeat perception tasks.

5.2 Method

5.2.1 Participants

15 healthy nonmeditators (10 men, 5 women) participated in the study (see **Table 5** for complete demographics). Nonmeditators were defined as individuals who had never received formal meditation training in meditation or yoga and did not practice self-taught meditation. All participants were screened for the presence of any neurological, psychiatric, cardiac or respiratory disease during a detailed phone interview, and were excluded if they reported a history of disease in any of these categories. None of the study participants were smokers, and none of the women took oral contraceptives or were pregnant, as assessed via urine pregnancy test. Each participant demonstrated a normal 12 lead electrocardiogram (EKG), as assessed by a board certified cardiologist or neurologist.

5.2.2 Tasks

Participants rated the experience of heartbeat and breathing sensations during and immediately following bolus infusions of isoproterenol and normal saline. Participants were told they would be receiving both isoproterenol and saline infusions, and were informed what the isoproterenol sensations might feel like (e.g., "you may notice your

heart beating faster, and/or may feel an increase in your breathing sensations"). They were not informed when they would be receiving each agent, but were verbally notified of the beginning of each infusion (e.g., "infusion starting"). Each infusion period lasted approximately 2 minutes. During each period participants were instructed to pay attention to their heartbeat and breathing sensations, and to rotate a dial to indicate their ongoing experience of the overall intensity of these body sensations. The dial could range from 0 ("normal, i.e., no change in intensity") to 10 ("most ever"). The dial was always set to zero at the beginning of each infusion, and participants were specifically instructed to keep the dial at zero if they felt they did not notice any increase in the intensity of heartbeat and breathing sensations above baseline. After each infusion, participants rated the intensity of heartbeat and breathing sensations they had experienced during the prior infusion period. In particular, they were instructed to rate via questionnaire the overall intensity of heartbeat and breathing sensations they had experienced during each infusion, from 0 ("normal, i.e., no change in intensity") to 10 ("most ever"), in the manner described by (Cameron and Minoshima, 2002).

Next, participants were instructed to rate the intensity of physical anxiety, mental anxiety, and distress experienced during each infusion using the same 0 to 10 rating scale. In an effort to calibrate each participant's understanding of the affective terminology employed, prior to infusion administration physical anxiety was operationalized as the "the bodily sensations you associate with the experience of being anxious," mental anxiety was operationalized as "worry, for example, the kind you might experience if you were running late for an important appointment," and distress was operationalized as "alarm, for example, the kind you might experience if you realized your house was on

fire and needed to escape".[5] Finally, participants were asked to place imaginary wagers on whether their heartbeat or breathing had changed during the preceding infusion period (e.g., "if you were going to bet that there was a change in your heartbeat [or breathing] induced by what you received through the IV, how much would you be willing to wager?") (Persaud et al., 2007). Any amount between 0 and 20 dollars could be wagered, and participants were instructed to bet 0 dollars if they were confident they had received a saline infusion.

Table 5. Nonmeditator demographic data.

Group demographics	
Sex	10 Men, 5 Women
Age (years)	37.0 +/- 12.8 (range: 19-60)
Body Mass Index	25.2 +/- 3.4 (range: 19.8-31.5)
Race	13 Caucasian American, 1 Asian American, 1 African American
Education (years)	15.7 +/- 2.1
Beck Anxiety Inventory score	3.9 +/- 4.0
Beck Depression Inventory score	3.9 +/- 5.3
Chronotropic Dose 25 (micrograms)	
Isoproterenol sensitivity test 1	4.88 +/- 2.65
Isoproterenol sensitivity test 2	6.99 +/- 6.15
Interoceptive rating trial	5.37 +/- 3.95

Chronotropic Dose 25 (CD25): dose of isoproterenol that would be required to increase the heart rate by 25 beats per minute. Means +/- standard deviation.

[5]These specific examples were chosen to reflect affective experiences that most individuals were either likely to have encountered in their own lives or could imagine as a realistic possibility.

5.2.3 Infusion protocol

Participants received 3 sets of isoproterenol infusions. The first two sets of infusions comprised a standard isoproterenol infusion challenge, which consisted of sequentially increasing isoproterenol doses of 0.1, 0.5, 1.0, 2.0 and 4.0 micrograms (mcg) (Cleaveland et al., 1972; Contrada et al., 1991; Martinsson et al., 1989; Mills et al., 1998; Yu et al., 2007). Participants were not instructed to rate the experience of interoceptive sensations during these infusions. These protocols were used to establish the chronotropic dose 25 (CD25), or the isoproterenol dose necessary to increase the participant's heart rate by 25 beats per minute above baseline. The CD25 is a commonly reported measure of beta adrenergic receptor sensitivity and was calculated by extrapolation from the slope of a linear regression at each individual's isoproterenol induced heart rate response (mean heart rate response at each isoproterenol dose minus baseline heart rate) (Arnold and McDevitt, 1983; Cleaveland et al., 1972; Mills et al., 1998; Yu et al., 2007). This administration order also ensured that each participant was familiar with the sensations elicited by isoproterenol prior to collection of interoceptive ratings. The third set of infusions comprised the interoceptive rating condition, which consisted of a total of 12 randomized infusions: 6 normal saline and 6 isoproterenol (0.1, 0.25, 0.5, 0.75, 1.0 and 2.0 mcg). The decision not to include a 4.0 mcg dose in the interoceptive rating condition was based on preliminary testing with a different sample of participants, in which I found that all participants reported changes in awareness at the 2.0 mcg dose. I chose instead to replace the 4 mcg dose with a lower dose (0.25 mcg), in order to more effectively determine the minimum dose that would result in changes in interoceptive awareness. The CD25 for this third set of infusions was also calculated, for

comparison with the first two sets of infusions. All infusions were administered a minimum of 3.5 minutes apart.

5.2.4 Infusion delivery

Each infusion (isoproterenol and saline) consisted of two 3 milliliter (ml) bolus infusions delivered sequentially through an intravenous catheter. During isoproterenol infusions, a 3 ml bolus containing the specified dose was delivered, immediately followed by a 3 ml bolus of saline to flush the line. During saline infusions, a 3 ml bolus of saline was delivered, immediately followed by an additional 3 ml bolus of saline. Both bolus volumes were administered in entirety within a 15 second period by a nurse from the General Clinical Research Center. This method of delivery minimized the participant's ability to use external cues to distinguish between the different infusion types, and ensured rapid and standardized systemic introduction of isoproterenol.

5.2.5 Procedure

The study involved one visit, which always started between 7 and 8am in the General Clinical Research Center (GCRC) at the University of Iowa. After completing the consent process participants filled out several questionnaires to assess demographics such as age, education, current levels of anxiety (Beck, 1990), depression (Beck, 1993), and positive and negative affective experience (Watson, 1988). Afterwards, a nurse measured each participant's height and weight, and female participants completed a urine pregnancy screen. The nurse then placed a 22 gauge intravenous catheter into the participant's non dominant dorsal hand vein, and administered a 12 lead EKG. A physician evaluated the EKG, and the experiment proceeded only if the EKG was considered normal (all recruited participants displayed normal EKGs). The participant

was led to a quiet room, seated in a comfortable chair, and was attached to leads for measuring heart rate (lead II EKG), respiratory rate (thoracic respiratory belt) and skin conductance response (non dominant thenar and hypothenar eminence). At this point the participant's non dominant hand was placed outstretched on a pillow at chest level. A curtain was positioned with the participant on one side and the nurse and the experimenter on the other side, to prevent the participant from viewing the preparation and administration of each infusion. The nurse then measured the participant's blood pressure and began the isoproterenol infusion protocol. Participants were instructed not to recline in the chair during each infusion period, in order to prevent them from using the back of the chair as an external source to help them detect heartbeat sensations. The entire testing session lasted approximately four hours. This study was approved by the GCRC Advisory Committee and the Institutional Review Board of the University of Iowa, and all participants provided informed consent prior to participation.

5.2.6 Psychophysiological measures

All physiological data including heart rate were recorded continuously during all infusions with an MP100 acquisition unit (Biopac Systems, Inc) at a sampling rate of 200 Hertz. Dial ratings were collected with a custom built dial that consisted of a rotating potentiometer with a continuous rating scale ranging from 0.000 to 5.000 Volts. The average heart rate change during each infusion was calculated across a 120 second interval immediately following the onset of each infusion. The average heart rate response was obtained by subtracting the average heart rate during the 30 second post infusion window (before isoproterenol induced heart rate changes had occurred) from the average heart rate during the subsequent 90 second window (when the isoproterenol

induced heart rate changes were most likely to occur). These windows were carefully chosen to coincide with the typical delays observed in the onset of isoproterenol induced heart rate changes due to the slow rate of venous drainage to the heart (Arnold and McDevitt, 1983; Cleaveland et al., 1972; Contrada et al., 1991; Mills et al., 1998; Yu et al., 2007). Peak heart rate changes were also calculated for each participant, defined as the maximum heart rate change occurring within a five second interval around the maximum heart rate change observed (during the 90 second infusion window) relative to the average heart rate during the 30 second baseline window. All artifacts affecting the instantaneous heart rate waveform (e.g., movement related, or due to premature ventricular contractions) were manually identified and removed.

Cross correlations for each participant were calculated from mean centered dial ratings and mean centered instantaneous heart rate changes occurring over the two minute interval following the onset of each infusion. This interval included the 30 second window following the infusion onset when isoproterenol induced HR changes had not yet occurred, as well as the subsequent 90 second window when isoproterenol induced heart rate changes were most likely. Dial ratings and instantaneous heart rate changes for each dose were mean centered by subtracting the 120 second mean for each infusion interval from each time point within that interval.

5.2.7 Data analysis

Single factor, repeated measures ANOVAs were performed with dose of isoproterenol as the independent measure and isoproterenol induced change scores as the dependent measure. Change scores were calculated by subtracting the mean value of all six saline responses from each isoproterenol response (Cleaveland et al., 1972; Contrada

et al., 1991). This approach provided a robust estimate of the baseline and enabled a sensitive determination of the effect of isoproterenol doses on deviations from baseline for each measure. If an overall significant effect of isoproterenol dose was detected, post hoc t-tests were performed using Tukey's HSD method to determine significant differences between the pairwise comparisons ($p = .05$ level). All measures were assessed for violations of the sphericity assumption, and when violated, were corrected with the Huynh-Feldt method. In these instances the corrected p values are reported, along with the Huynh-Feldt epsilon (ε) correction. Finally, Pearson's correlations were calculated to determine if relationships existed between isoproterenol sensitivity (CD25 and dose-specific heart rate responses), interoceptive ratings, and demographic factors such as age, BMI, reported levels of anxiety, depression and positive and negative affect.

5.3 Results

5.3.1 Heart rate response

A repeated measures ANOVA revealed a significant effect of isoproterenol on the mean heart rate response $F(5, 70) = 18.23$, $p < .0001$, $\eta_p^2 = .57$, $\varepsilon = .531$, indicating that isoproterenol infusions elicited increases in heart rate (**Figure 7A**). Post hoc testing revealed that the mean heart rate response significantly increased at the three highest doses of isoproterenol (0.75, 1.0 and 2.0 mcg). A repeated measures ANOVA also revealed a significant effect of isoproterenol on the peak heart rate response $F(5, 70) = 22.08$, $p < .0001$, $\eta_p^2 = .61$. Post hoc testing revealed that the peak heart rate response significantly increased at the four highest doses (0.5, 0.75, 1.0 and 2.0 mcg). The mean CD25 values obtained during the isoproterenol sensitivity tests and during the

interoceptive ratings are listed in **Table 1**. No significant differences in the CD25 values were observed across the three conditions $F(2, 28) = .09$, $p = .92$, suggesting that habituation to isoproterenol did not occur with repeated administration. The group's average heart rate during all saline infusions was 67.8 +/- 11.3 bpm.

5.3.2 Retrospective interoceptive ratings

A repeated measures ANOVA revealed a significant effect of isoproterenol on retrospective ratings of the overall intensity of heartbeat sensations $F(5, 70) = 20.1$, $p < .0001$, $\eta_p^2 = .59$, $\varepsilon = .44$, indicating that isoproterenol infusions elicited greater changes in awareness of heartbeat sensations than saline (**Figure 7B**). Post hoc testing revealed that increased ratings of heartbeat sensations occurred at the three highest doses (0.75, 1.0 and 2.0 mcg).

A repeated measures ANOVA revealed a significant effect of isoproterenol on retrospective ratings of the overall intensity of breathing sensations $F(5, 70) = 10.1$, $p < .0002$, $\eta_p^2 = .42$, $\varepsilon = .496$, indicating that isoproterenol infusions elicited greater changes in awareness of breathing sensations than saline (**Figure 7E**). Post hoc testing revealed that increased ratings of breathing sensations occurred at the three highest doses (0.75, 1.0 and 2.0 mcg).

5.3.3 Post infusion wagering

A repeated measures ANOVA revealed a significant effect of isoproterenol on post infusion wagering on heartbeat change $F(5, 70) = 19.37$, $p < .0001$, $\eta_p^2 = .58$, indicating that isoproterenol infusions elicited greater changes in wagering amounts than saline (**Figure 7C**). Post hoc testing revealed that increased wagering on heartbeat change occurred at the three highest doses (0.75, 1.0 and 2.0 mcg).

A repeated measures ANOVA revealed a significant effect of isoproterenol on post infusion wagering on breathing change $F(5, 70) = 21.2$, $p < .0001$, $\eta_p^2 = .60$, indicating that isoproterenol infusions elicited greater changes in wagering amounts than saline (**Figure 7F**). Post hoc testing revealed that increased wagering on breathing change also occurred at the three highest doses (0.75, 1.0 and 2.0 mcg).

5.3.4 Online dial ratings

Figure 8A shows the observed mean heart rate and corresponding mean dial ratings produced by all participants throughout each 120 second infusion interval, for all doses of isoproterenol. In this figure, dial ratings have been normalized by scaling the dial rating amplitude for each dose to each participant's maximum heart rate change observed during the 2.0 mcg dose, according to the following formula: normalized instantaneous dial rating = instantaneous heart rate at initial sample + maximum heart rate change at 2.0 mcg x (instantaneous dial rating/5.000). As a result, possible dial rating amplitudes range from a minimum of 0 to a maximum of the peak heart rate observed during the 2.0 mcg dose.

A repeated measures ANOVA revealed a significant effect of isoproterenol on the zero order cross correlation $F(5, 70) = 3.85$, $p = .004$, $\eta_p^2 = .22$, indicating that participants generated greater zero lag cross correlations at increasing doses of isoproterenol (**Figure 8B**). Post hoc testing revealed that participants generated increased zero order cross correlations only at the highest dose (2.0 mcg). A repeated measures ANOVA revealed a significant effect of isoproterenol on the maximum cross correlation $F(5, 70) = 14.85$, $p < .0001$, $\eta_p^2 = .52$, indicating that participants generated greater maximum cross correlations (irrespective of lag) at increasing doses of isoproterenol

(**Figure 8C**). Post hoc testing this time revealed that participants generated increased maximum cross correlations at the four highest doses (0.5, 0.75, 1.0 and 2.0 mcg). A secondary analysis examined whether the absolute value of the lag times obtained at the maximum cross correlation differed for the isoproterenol infusions. A repeated measures ANOVA revealed a significant effect of isoproterenol on the absolute lag times $F(5, 70) = 2.46$, $p = .041$, $\eta_p^2 = .15$, indicating that participants generated lower lag times at increasing doses of isoproterenol (**Figure 8D**). Post hoc testing revealed participants generated lower lag times only at the highest dose (2.0 mcg).

5.3.5 Interoceptive sensation frequency

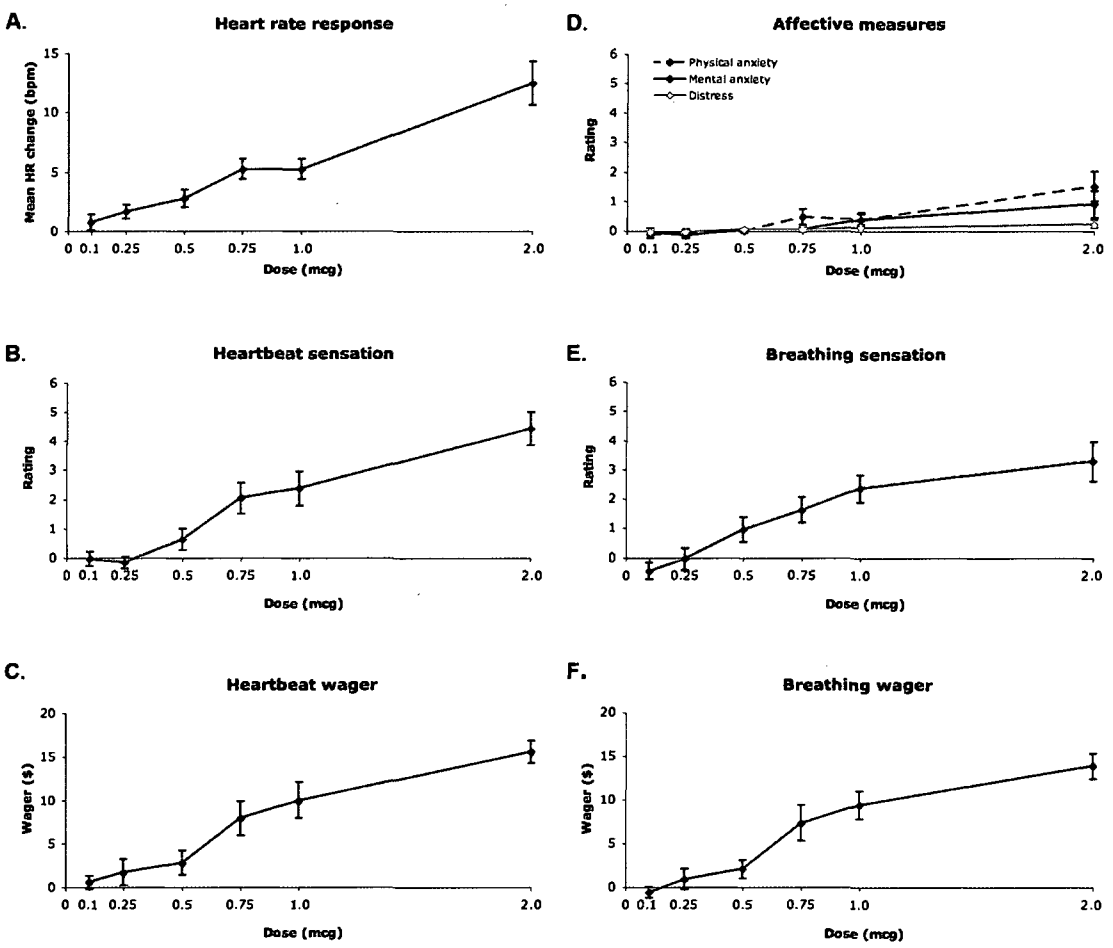
Examination of the individual online dial ratings revealed that increasing numbers of participants perceived increases in heartbeat and breathing sensations at increasing doses (**Figure 9A**). Not surprisingly, the lowest increases in sensation were reported during the saline infusions (30% of all saline trials administered). A minority of participants perceived increased interoceptive sensations at the two lower doses (0.1, 0.25 mcg) whereas a majority of participants perceived increased interoceptive sensations at the four highest doses (0.5, 0.75, 1.0 and 2.0 mcg). Every single participant (15/15) perceived increases in sensation at the highest dose (2.0 mcg), and the peak sensation ratings at this dose were highly correlated with the observed peak heart rate changes ($r = .746$, $p = .001$) (**Figure 9B**).

5.3.6 Affective measures

A repeated measures ANOVA revealed a significant effect of isoproterenol on ratings of physical anxiety $F(5, 70) = 6.28$, $p = .01$, $\eta_p^2 = .31$, $\varepsilon = .328$. Post hoc testing revealed that increased ratings of physical anxiety occurred only at the highest dose (2.0

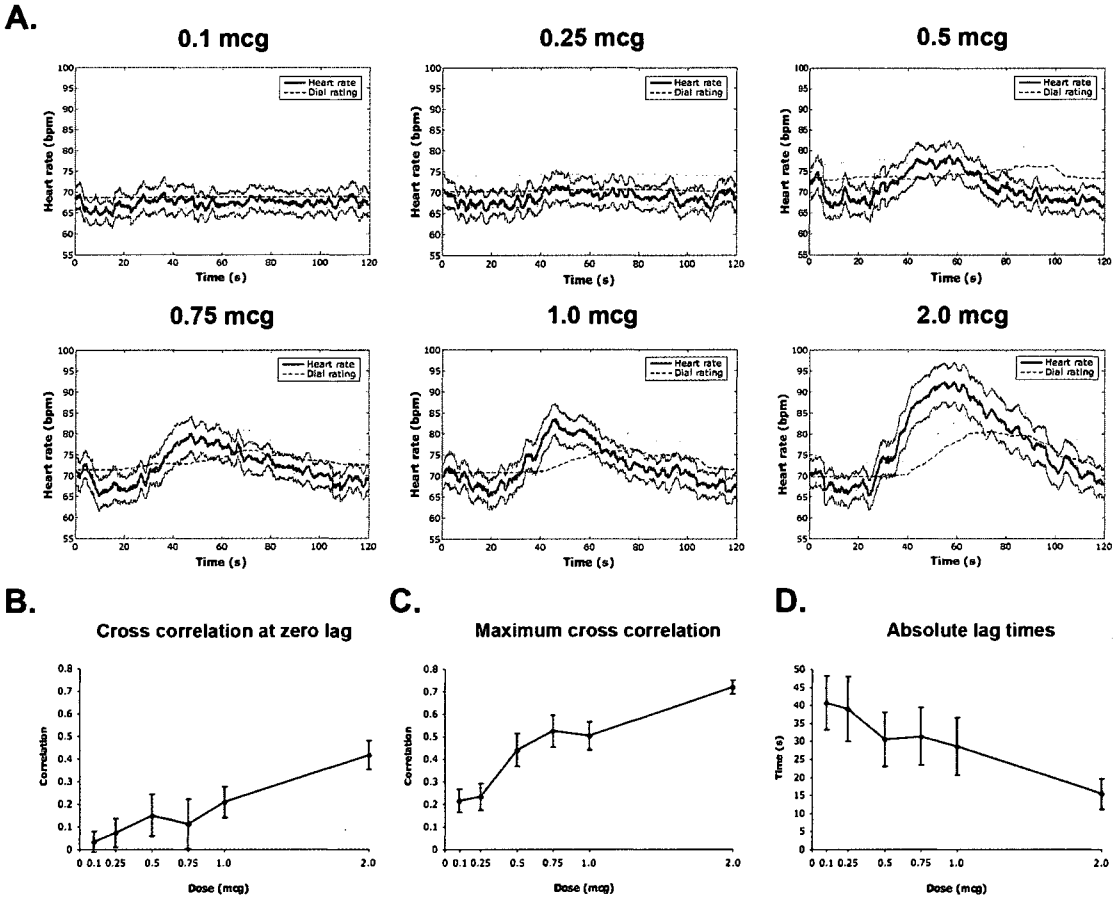
mcg). There were no significant increases in the ratings of mental anxiety $F(5, 70) = 2.97$, $p < .10$, $\varepsilon = .248$, or distress $F(5, 70) = 2.15$, $p < .15$, $\varepsilon = .314$ (**Figure 7D**). There were no significant correlations between the CD25 values obtained during any of the isoproterenol administrations and age, BMI, level of anxiety (assessed prior to infusion administration via Beck Anxiety Inventory) depression (Beck Depression Inventory), or positive and negative affect.

Figure 7. Heart rate response and retrospective interoceptive ratings.



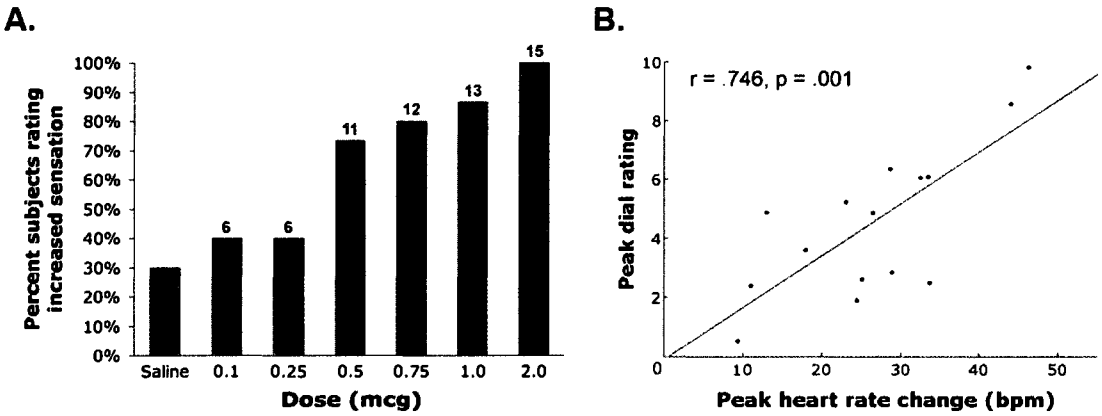
(A) Mean heart rate response. (B) Retrospective ratings of the intensity of heartbeat sensations (scale: 0 = 'normal' to 10 = 'most ever'). (C) Post infusion wagering on the presence of heartbeat change during each infusion. (E) Retrospective ratings of the intensity of breathing sensations (scale: 0 = 'normal' to 10 = 'most ever'). (F) Post infusion wagering on the presence of breathing change during each infusion. (D) Affective measures (scale: 0 = 'normal' to 10 = 'most ever'). Means +/- SE.

Figure 8. Time course of heart rate and interoceptive dial ratings.



(A) Mean time course of heart rate at each dose (thick black line) and associated normalized dial rating (thick dashed gray line) for all participants. Thin lines indicate SE. (B) Cross correlation between objective heart rate increases induced by isoproterenol and subjective online ratings of the intensity of heartbeat and breathing sensations at zero lag. (C) Maximum cross correlation. (D) Absolute lag times at maximum cross correlation.

Figure 9. Percent reporting increases in interceoptive sensations.



(A) Percentage of participants rating increases in interoceptive sensations at each dose. A participant was considered to have endorsed an increase in sensation above baseline if they turned the dial above zero at any point during the 90 second infusion period. The numbers at the top of the bars denote the number of participants endorsing increased sensation at each dose. (B) Correlation between the peak dial rating of the intensity of interoceptive sensations and the peak heart rate change during the highest dose (2.0 mcg) for each participant. Dial rating scale: 0 = 'normal' to 10 = 'most ever'.

5.4 Discussion

As expected, bolus isoproterenol infusions elicited rapid and transient dose-dependent increases in heart rate. These increases were evident across the mean as well as peak heart rate responses. Significant increases in mean heart rate were observed at the three highest doses (0.75, 1.0 and 2.0 mcg), whereas increases in peak heart rate were observed at the four highest doses (0.5, 0.75, 1.0 and 2.0 mcg). The calculated CD25 values from the isoproterenol sensitivity tests and the interoceptive rating condition suggest that the levels of bodily change observed in the current study are similar to those commonly reported in the literature (Mills et al., 1998; Yu et al., 2007).

Concomitant with these changes in peripheral body state, bolus isoproterenol infusions elicited changes in cardiac and respiratory sensations. Increases in

interoceptive awareness were observed at increasing doses of isoproterenol, as indexed by retrospective ratings, post infusion wagering, and continuous dial ratings. Interestingly, these increases in interoceptive awareness were indexed to a somewhat different extent by each rating method. Retrospective ratings of interoceptive sensations and post infusion wagering indicated that increased awareness of both heartbeat and breathing sensations occurred at the three highest doses (0.75, 1.0 and 2.0 mcg), perhaps suggesting that these two tasks draw upon a similar type of information when utilized in a retrospective fashion. In contrast, after accounting for the lag time, the cross correlations measured via continuous dial ratings indicated that increases in interoceptive awareness occurred at the four highest doses (0.5, 0.75, 1.0, and 2.0 mcg). Since heart rate changes were observed at the four highest doses of isoproterenol, it appears that the continuous dial ratings provided a more sensitive measure for detecting changes in interoceptive awareness than retrospective ratings. This is understandable given that the dial rating method provides a higher resolution scale for reporting momentary and/or subtle changes in interoceptive sensation, over a more nuanced window of time (e.g., continuous online versus single retrospective). Nevertheless, from the observed lag times it also appears that there are significant delays between the objective changes in body state and subjective perceptions of these changes, even for doses that readily elicit increases in interoceptive awareness. These delays are consistent with findings from other modalities of visceral sensation such as gastrointenstinal distension, in which the time course and quality of visceral sensations correlate imperfectly with visceral stimulation (Aziz et al., 2000; Cervero, 1985; Holzl et al., 1996). Identifying the neurophysiological mechanisms underlying these multimodal delays in awareness represents an important area for further

investigation, one that may yield critical insights into the neural basis of interoceptive awareness.

At the four highest doses of isoproterenol (0.5, 0.75, 1.0 and 2.0 mcg) the majority of nonmeditators perceived increased interoceptive sensations, and at the highest dose all nonmeditators reported increases in interoceptive sensations. In addition, the degree to which these sensations were perceived was highly correlated with the degree of observed heart rate change at the highest dose. These findings indicate that the current method has overcome a major limitation of previous methods, for example, the widely reported finding of less than 40% accuracy rates for resting heartbeat detection tasks. Specifically, the current method appears to provide the capacity to reliably manipulate and measure awareness of interoceptive sensations in most if not all participants. Accordingly, instead of being limited to examining differences between good and bad heartbeat detectors (or perceivers), the relationship between interoceptive sensations and meditation (or any other variable under investigation) might be measurable in every participant, and for varying levels of interoceptive awareness. An additional benefit of the present method relates to improved ecological validity: rather than abstractly comparing heartbeat sensations to tones or counting heartbeats, participants simply indicate the degree to which their interoceptive sensations are changing in real time. Furthermore, they do so in a manner that shares closer phenomenological proximity to the experience of naturally occurring changes in levels of physiological arousal that, notably, also arise within the context of emotional experience.

Isoproterenol doses elicited a small increase in retrospective ratings of physical anxiety but did not elicit increased ratings of mental anxiety or distress, indicating that

the effects of the bolus isoproterenol infusions were disproportionately restricted to experiences of physical body sensations. The observed pattern of findings is somewhat different from the ratings reported by Cameron & Minoshima (2002), who found that a continuous 30 minute infusion of isoproterenol titrated to a heart rate of 120 bpm resulted in increased ratings of anxiety and distress. Since the current study utilized lower doses of isoproterenol and in a bolus format, few participants' heart rates ever reached 120 bpm (peak heart rate reached 120 bpm for only 2 of the 15 participants). As a result, participants in the current study experienced smaller changes in arousal and for briefer periods of time. However, these changes were an intended feature of the design: they were aimed at better mimicking the transient aspect of emotions, and were in light of the fact that extreme changes in arousal are not required for an experience to be reported as emotional (Ben-Ze'ev, 2000; Davidson, 2003; Hutcherson et al., 2005). In the Cameron & Minoshima (2002) study, the duration and magnitude of the heart rate increase was such that participants may have generated anxiety about being in this state for so long, with potential distress due to the lack of controllability over such an extended elevation in the state of arousal. Thus it is possible that the reported anxiety might have not been the direct reflection of the physiological activation (as would be predicted in a James-Lange theoretical framework), but rather a secondary development of an emotional state. It is interesting to note that in the current study, participants only perceived the intensity of interoceptive sensations as moderate at the maximum dose (on average not exceeding 5 on a scale of 10). Future studies could address whether reports of anxiety or other emotions can be induced at higher doses approximating or even exceeding the heart rate changes observed by Cameron & Minoshima (2002).

In a broader context, the fact that transient changes in peripheral arousal were not sufficient to induce negatively valenced affective states would appear to argue against a literal interpretation of the James-Lange theory. However, the current study was not specifically designed to tackle this issue, and thus the comment here should be taken as speculative. It is only mentioned as a possibility because the current method provides a powerful tool for evaluating the roles that interoceptive awareness have been proposed to play in the experience of emotional states. Thus one benefit of this method could allow for investigations of the degree to which the elicited patterns of cardiorespiratory responses are capable of inducing primary and secondary emotions, as suggested by the James-Lange theory. Similarly, by combining the current method with adequate manipulations of emotional context (a la Schacter & Singer, 1962), novel insights could be generated that refine our understanding of the relative influences of interoceptive and cognitive states on the subjective experience of emotion. Yet another viable area of inquiry relates to the extent to which interoceptive sensations are at all relevant for emotional states (a la Rolls, 2000; i.e., whether they are a necessary component or are merely a downstream consequence of emotional processing).

Nevertheless, at a basic level, the current method provides a framework for investigating the connections between meditation and interoceptive awareness.

CHAPTER 6. THE EFFECT OF MEDITATION ON AWARENESS OF INTERNAL BODY SENSATIONS

6.1 Background

The previous study demonstrated that bolus isoproterenol infusions provided a better method for assessing interoceptive awareness than heartbeat detection, facilitating a continued investigation of the putative link between meditation and interoceptive awareness. Consequently, the current study again examined interoceptive awareness in experienced meditators, this time using the bolus isoproterenol infusion protocol.

Several insights gleaned from the initial study of experienced meditators guided the current study design. First, since there is variability in the manner in which different meditation traditions cultivate interoceptive awareness, I decided to recruit individuals primarily from meditation traditions that specifically emphasize the importance of body sensations. Consequently, I recruited the majority of meditators from the Vipassana tradition. I chose the Vipassana tradition because it places a large emphasis on cultivating attention to internal body sensations from the very beginning of the practice, and specifically teaches that the meditation practice results in an increased awareness of and self control over the body ((Hart, 1987), also see www.dharma.org/ims/index.htm and www.dhamma.org/vipassan.htm). Secondly, since it is possible that awareness of heartbeat sensations alone is a poor index of the type of interoceptive sensations cultivated by the practice of meditation, I made sure that isoproterenol protocol also allowed for assessment of other interoceptive sensations such as breathing. Finally, since the cultivation of interoceptive sensations is more often emphasized during earlier phases of training, I allowed meditators with lower amounts of practice experience into the

study. Although this was the primary reason, two additional considerations related to (a) the difficulty associated with recruiting a sample meditatiors with as much experience as those from the first study and (b) the concern that meditators with such lengthy amounts of training were less representative of the general population of meditators.

Based on the hypothesis that the long term practice of meditation is associated with an increase in interoceptive awareness, I predicted that meditators would display increased interoceptive awareness at lower doses of isoproterenol than nonmeditators (indexed via the same retrospective and online measures utilized previously). I also predicted that, at doses for which the majority of participants in both groups generated awareness, meditators would be more accurate than nonmeditators at tracking the ongoing experience of interoceptive sensations (indexed via the maximum cross correlation).

6.2 Method

6.2.1 Participants

15 nonmeditators and 15 meditators participated in the study. Each nonmeditator was individually matched to a corresponding meditator based on three criteria: age, gender and body mass index (see **Table 6** for complete demographics). 11 of the meditators were Vipassana practitioners, and the other four meditators were Kundalini practitioners. Meditators were considered eligible for participation if they reported a continuous (daily or near daily) meditation practice during the previous two years, and if they had also attended one or more weeklong meditation retreats within the previous year. Nonmeditators were considered eligible for participation if they had never received

formal meditation training in meditation or yoga and did not practice self-taught meditation.[6]

All participants were screened for the presence of any neurological, psychiatric, cardiac or respiratory disease during a detailed phone interview, and were excluded if they reported a history of disease in any of these categories. None of the study participants were smokers, and none of the women took oral contraceptives or were pregnant, as assessed via urine pregnancy test. Each participant demonstrated a normal 12 lead electrocardiogram (EKG), as assessed by a board certified cardiologist or neurologist.

6.2.2 Tasks

Each participant rated the experience of internal body sensations both during and following multiple bolus infusions of isoproterenol. The procedure for measuring interoceptive awareness was identical to the procedure described in the previous chapter, and as a result the description of the protocol has been abbreviated (see **Chapter 5** for a full description of the protocol).

During each infusion, participants indicated their ongoing (moment-to-moment) experience of the intensity of heartbeat and breathing sensations. After each infusion, participants provided retrospective ratings of the intensity of heartbeat and breathing sensations. Participants were then instructed to trace as accurately as possible on a manikin template the locations where they had felt heartbeat sensations within their own body. If they felt that they had not felt an increase in their heartbeat sensation (for example, during a saline infusion), they were instructed to leave the manikin untraced.

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[6]This group of nonmeditators included the majority of the nonmeditators from the previous study. These nonmeditators were carried over for demographic matching purposes, in order to facilitate comparisons between meditators and nonmeditators.

Next, participants rated their affective experience during the infusion (physical/mental anxiety and distress), and, finally, placed imaginary wagers on the presence of heartbeat and breathing change. Meditators were asked not to meditate during the task, and were instructed to keep their eyes open throughout the rating period.

6.2.3 Data analysis

2 x 6 repeated measures ANOVAs were performed on each univariate dependent variable of interest, with group (meditators, nonmeditators) as the between subjects factor and with dose of isoproterenol as the within subjects factor. All univariate repeated measures ANOVA tests were assessed for violations of the sphericity assumption, and when violated, were corrected with the Huynh-Feldt method. In these instances the corrected p values are reported, along with the Huynh-Feldt epsilon (ε) correction.

Table 6. Meditator and nonmeditator demographic data.

	Meditators (M)	Nonmeditators (NM)
Sex	10 Men, 5 Women	10 Men, 5 Women
Age (yrs)	44.7 +/- 13.2	44.0 +/- 13.7
Body Mass Index	24.5 +/- 4.6	25.5 +/- 4.0
Race	15 Caucasian American	14 Caucasian American, 1 Asian American
Education (years)	17.3 +/- 2.2	15.9 +/- 2.3
Beck Anxiety Inventory score	5.1 +/- 3.4	3.5 +/- 2.9
Beck Depression Inventory score	4.3 +/- 4.6	3.7 +/- 5.3
Meditation practice (yrs)	10.8 +/- 10.8	0 +/- 0
Cumulative meditation practice (hrs)	4947 +/- 6251	0 +/- 0
Retreat experience (days)	19 +/- 14	0 +/- 0
CD25 (micrograms)	4.48 +/- 1.5	4.72 +/- 2.2

Means +/- standard deviation.

6.3 Results

6.3.1 Participants

Meditators reported significantly more years of meditation practice $t(28) = 3.90$, $p = .002$, hours of cumulative meditation practice $t(28) = 3.07$, $p = .008$, and days of retreat experience $t(28) = 2.31$, $p = .037$, than nonmeditators. The groups did not differ with respect to age $t(28) = .15$, $p = .88$, body mass index $t(28) = -.63$, $p = .53$, or education $t(28) = 1.64$, $p = .11$. The groups also did not differ with respect to baseline levels of anxiety (assessed via the Beck Anxiety Inventory) $t(28) = 1.39$, $p = .18$, or depression (assessed via the Beck Depression Inventory) $t(28) = .33$, $p = .74$.

6.3.2 Heart rate response

A 2 x 6 repeated measures ANOVA revealed a main effect of dose $F(1, 5) = 50.10$, $p < .0001$, $\eta_p^2 = .64$, $\varepsilon = .807$, indicating that increasing doses of isoproterenol elicited increases in mean heart rate response. There was no effect of group $F(1, 28) = 1.27$, $p = .27$, $\eta_p^2 = .04$, and there was no group by dose interaction $F(1, 5) = .04$, $p = .998$, $\eta_p^2 = .00$, indicating that isoproterenol infusions elicited equivalent increases in heart rate in both groups (**Figure 10**). An independent samples t test of CD25 values also did not reveal any group differences in heart rate reactivity to isoproterenol: $t(28) = -.35$, $p = .73$. Finally, there were no group differences in average heart rate during the saline infusions: $t(28) = .25$, $p = .80$.

6.3.3 Retrospective interoceptive ratings

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on ratings of heartbeat sensations $F(1, 5) = 47.35$, $p < .0001$, $\eta_p^2 = .63$, $\varepsilon = .446$, indicating that increasing doses of isoproterenol elicited greater increases in the intensity of

heartbeat sensations than saline. However, there was no effect of group $F(1, 28) = .49$, $p = .49$, $\eta_p^2 = .02$, and there was no group by dose interaction $F(1, 5) = 1.23$, $p = .30$, $\eta_p^2 = .04$, indicating that there were no group differences in the perceived change in intensity of heartbeat sensations (**Figure 11**).

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on ratings of breathing sensations $F(1, 5) = 22.08$, $p < .0001$, $\eta_p^2 = .44$, $\varepsilon = .597$, indicating that increasing doses of isoproterenol elicited greater increases in the intensity of breathing sensations than saline. However, there was no effect of group $F(1, 28) = .74$, $p = .40$, $\eta_p^2 = .03$, and there was no group by dose interaction $F(1, 5) = 1.29$, $p = .28$, $\eta_p^2 = .04$, indicating that there were no group differences the perceived change in intensity of breathing sensations (**Figure 12**).

6.3.4 Post infusion wagering

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on post infusion wagering on heartbeat change $F(1, 5) = 33.11$, $p < .0001$, $\eta_p^2 = .54$, $\varepsilon = .889$, indicating that isoproterenol infusions elicited greater changes in wagering amounts than saline. However, there was again no effect of group $F(1, 28) = ..01$, $p = .91$, $\eta_p^2 = .00$, and there was no group by dose interaction $F(1, 5) = .72$, $p = .60$, $\eta_p^2 = .03$, indicating that the groups did not differ in their willingness to place wagers on the presence of heartbeat change (**Figure 13**).

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on post infusion wagering on breathing change $F(1, 5) = 28.59$, $p < .0001$, $\eta_p^2 = .51$, indicating that isoproterenol infusions elicited greater changes in wagering amounts than saline. There was again no effect of group $F(1, 28) = .55$, $p = .47$, $\eta_p^2 = .02$, and there was no

group by dose interaction $F(1, 5) = .47$, $p = .76$, $\eta_p^2 = .02$, indicating that the groups did not differ in their willingness to place wagers on the presence of breathing change (**Figure 14**).

6.3.5 Online dial ratings

Figures 15 and **16** show the observed mean heart rate and corresponding mean dial ratings produced by all participants throughout each 120 second infusion interval, for all doses of isoproterenol. In these figures, dial ratings have been normalized by scaling the dial rating amplitude for each dose to each participant's maximum heart rate change observed during the 2.0 mcg dose, according to the following formula: normalized instantaneous dial rating = instantaneous heart rate at initial sample + maximum heart rate change at 2.0 mcg x (instantaneous dial rating/5.000). As a result, possible dial rating amplitudes range from a minimum of 0 to a maximum of the peak heart rate observed during the 2.0 mcg dose.

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on the zero order cross correlation $F(1, 5) = 15.37$, $p < .0001$, $\eta_p^2 = .35$, $\varepsilon = .857$, indicating that participants generated greater zero lag cross correlations at increasing doses of isoproterenol. However, there was again no effect of group $F(1, 28) = 2.99$, $p = .10$, $\eta_p^2 = .10$, and there was no group by dose interaction $F(1, 5) = 1.06$, $p = .38$, $\eta_p^2 = .04$, indicating that there were no group differences in the online tracking of interoceptive sensations (**Figure 17**).

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on the maximum cross correlation $F(1, 5) = 39.92$, $p < .0001$, $\eta_p^2 = .59$, indicating that participants generated greater maximum cross correlations at increasing doses of

isoproterenol. There was no effect of group $F(1, 28) = 0.00$, $p = .99$, $\eta_p^2 = .00$, and there was a nearly significant group by dose interaction $F(1, 5) = 2.23$, $p = .06$, $\eta_p^2 = .07$, indicating that there were no group differences in the online tracking of interoceptive sensations (**Figure 18**).

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on the absolute lag times $F(1, 5) = 11.81$, $p < .0001$, $\eta_p^2 = .30$, $\varepsilon = .756$, indicating that participants generated lower absolute lag times at increasing doses of isoproterenol. There was no effect of group $F(1, 28) = 1.04$, $p = .32$, $\eta_p^2 = .04$, and there was no group by dose interaction $F(1, 5) = .24$, $p = .91$, $\eta_p^2 = .01$, indicating that there were no group differences in the online tracking of interoceptive sensations (**Figure 19**).

6.3.6 Interoceptive sensation frequency

Examination of the individual online dial ratings revealed that for both meditators and nonmeditators, increasing numbers of participants perceived increases in heartbeat and breathing sensations at increasing doses (**Figure 20**). The lowest increases in sensation were reported during the saline infusions (28% of all saline trials for the nonmeditators versus 31% for the meditators). A minority of the meditators perceived increased interoceptive sensations at the three lowest doses (0.1, 0.25, 0.5 mcg) whereas a majority of the meditators perceived increased interoceptive sensations at the three highest doses (0.75, 1.0 and 2.0 mcg). A minority of the nonmeditators perceived increased interoceptive sensations at the three lowest doses (0.1, 0.25, 0.5 mcg) whereas a majority of the meditators perceived increased interoceptive sensations at the four highest doses (0.5, 0.75, 1.0 and 2.0 mcg). Every single participant (15/15) in both groups perceived increases in sensation at the highest dose (2.0 mcg).

6.3.7 Peak ratings

Since all participants reported an increase in sensations at the highest dose, peak heart rate changes and peak interoceptive ratings were examined for group differences. There were no group differences in peak heart rate change $t(28) = .84$, $p = .41$, or peak dial rating $t(28) = .81$, $p = .43$. For the nonmeditators, the peak sensation ratings at this dose were highly correlated with the observed peak heart rate changes ($r = .864$, $p = .0001$). In contrast, for the meditators, the peak sensation ratings at the highest dose were uncorrelated ($r = .281$, $p = .310$) (**Figure 21**).

6.3.8 Affective measures

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on ratings of physical anxiety $F(1, 5) = 12.16$, $p < .0001$, $\eta_p^2 = .38$, $\varepsilon = .419$, indicating that participants experienced an increase in physical anxiety at increasing doses of isoproterenol. There was no effect of group $F(1, 28) = .13$, $p = .72$, $\eta_p^2 = .01$, and there was no group by dose interaction $F(1, 5) = .55$, $p = .59$, $\eta_p^2 = .03$, indicating that the groups did not differ in their experience of physical anxiety (**Figure 22**).

A 2 x 6 repeated measures ANOVA revealed a significant effect of dose on ratings of physical anxiety $F(1, 5) = 2.73$, $p = .04$, $\eta_p^2 = .12$, $\varepsilon = .711$, indicating that participants experienced a small increase in mental anxiety at increasing doses of isoproterenol. There was no effect of group $F(1, 28) = .90$, $p = .35$, $\eta_p^2 = .04$, and there was no group by dose interaction $F(1, 5) = 1.01$, $p = .40$, $\eta_p^2 = .05$, indicating that the groups were not different in their experience of mental anxiety (**Figure 23**).

A 2 x 6 repeated measures ANOVA did not reveal any effect of dose on ratings of distress $F(1, 5) = 1.78$, $p = .16$, $\eta_p^2 = .08$, $\varepsilon = .600$, indicating that participants did not

experience any increases in distress at increasing doses of isoproterenol. There was also no effect of group $F(1, 28) = .26$, $p = .61$, $\eta_p^2 = .01$, and there was no group by dose interaction $F(1, 5) = .31$, $p = .82$, $\eta_p^2 = .02$ (**Figure 24**).

6.3.9 Post analysis

Average cross correlations were computed for the three lowest (0.1, 0.25, 0.5 mcg) and three highest (0.75, 1.0, 2.0 mcg) doses for each group. Since the majority of individuals in both groups reported increases in sensation at the three highest doses, only the highest doses were compared for differences.[7] This time there was a significant difference between the mean zero order cross correlation for the three highest doses: one tailed $t(28) = 1.83$, $p = .04$, indicating that on average, meditators generated greater zero cross correlations across these doses (**Figure 25A**). However, when accounting for the lag time there was no difference in the mean maximum cross correlation: one tailed $t(28) = .46$, $p = .32$ (**Figure 25B**). There was also no significant difference in the mean lag time at these doses: one tailed $t(28) = 1.34$, $p = .10$ (**Figure 25C**). Since the zero order cross correlation is sensitive to temporal shifts between the signals being compared, a final component of the analysis examined whether the group difference in zero order cross correlations at the higher doses was related to differences in the timing of dial ratings (**Figure 26A**). The peak to peak delay (in this case, the peak dial rating relative to the peak heart rate change) was analyzed. Limited evidence for this possibility was found at the higher doses, in the form of a trend towards shorter peak to peak delays in the meditators (one tailed $t(28) = -1.40$, $p = .09$) (**Figure 26B**).

[7] For this analysis, any values from subjects who did not turn the dial above zero were excluded, as this would have artificially lowered the zero order cross correlations and increase the lag time for each group.

6.3.10 Heartbeat sensation locations

Overlap maps of the locations of perceived heartbeat sensations at each infusion are plotted for the nonmeditators and meditators in **Figure 27**. These maps indicate that as the dose of isoproterenol increased, a greater number of participants in each group localized heartbeat sensations to regions within their body. Nonmeditators perceived heartbeat sensations in the anterior chest, particularly in the lower left region. There was also some variability in the localization of the heartbeat sensation, with a few nonmeditators also perceiving heartbeat sensations in the head, abdomen and arms. Meditators also perceived heartbeat sensations in the chest, but with greater frequency in the midline. There also appeared to be greater variability in localization of heartbeat sensations, with greater numbers of meditators reporting sensations in body regions such as the neck, abdomen, head, back, arms and legs. Group differences in location of heartbeat sensation are displayed in **Figure 28**. This overlap difference map shows that more meditators reported experiencing heartbeat sensations in the neck ($\geq$ 8 difference in favor of meditators, or $\geq$ 50% difference) and abdomen ($\geq$ 4 difference in favor of meditators, or $\geq$ 25% difference), whereas more nonmeditators reported experiencing heartbeat sensations in the lower left anterior chest ($\geq$ 5 difference in favor of nonmeditators, or $\geq$ 33% difference). This pattern of differences was also present in the saline condition, both groups generated far fewer overlaps of heartbeat sensations following saline infusions.

6.4 Discussion

As expected, bolus isoproterenol infusions elicited dose-dependent increases in heart rate in both groups, and elicited concomitant changes in cardiac and respiratory sensations, as indexed by retrospective ratings, post infusion wagering, and continuous dial ratings. However, contrary to expectations, meditators did not exhibit increased awareness of interoceptive sensations. There were no group differences observed in any of the first pass measures employed, including retrospective ratings, post infusion wagering, or cross correlations of continuous dial ratings. The lack of group differences in these global measures of sensation occurred even at the highest dose, for which all participants correctly endorsed changes in interoceptive awareness. A secondary analysis of the three highest doses combined (for which a majority of individuals in both groups reported increased interoceptive sensation) did reveal a group difference in the zero order cross correlations. Further examination of the time course of dial ratings revealed that meditators had a tendency to rate the onset of interoceptive changes sooner and reach the peak intensity rating sooner. However, this group difference was not maintained after accounting for the lag time. Isoproterenol infusions also elicited smaller increases in ratings of physical and mental anxiety, although there were again no group differences in these affective measures.

The absence of an effect cannot be ascribed to an inability of most subjects to experience interoceptive sensations (a primary limitation of the initial heartbeat detection study). Participants in both groups experienced equivalent increases in mean heart rate change, and there were no differences in isoproterenol reactivity as measured by CD25 values. Both groups of participants appropriately perceived increases in heartbeat and

breathing sensations at increasing doses, for all utilized indices. At the highest dose all participants endorsed an increase in interoceptive sensations. Furthermore, there were no group differences in peak heart rate or peak dial ratings at this dose. One difference that was seen related to the peak intensity of reported sensation at the highest dose, which was highly correlated with the observed peak heart rate change for the nonmeditators, but not the meditators.

Several differences were also observed that neared or reached the threshold for statistical significance. The first relates to a nearly significant group difference in zero cross correlations ($p = .1$), which, after restricting a secondary analysis to the highest doses became significant ($p = .04$). The second relates to a group by dose interaction in the maximum cross correlations ($p = .06$). Given the directional nature of the hypothesis, it is compelling to want to highlight these differences as evidence of increased awareness in the meditators. However, if one were to assume these findings were significant, a careful inspection of this pattern of results would in fact argue against the hypothesis. Consider the following rationale for the group differences in zero order cross correlation. Since the zero order cross correlation is relatively more affected than the maximum cross correlation by offsets in the timing between heart rate change and dial rating, this pattern would suggest that the meditators were simply less delayed in reporting changes in interoceptive sensations than nonmeditators. Limited evidence was found for this possibility in favor of the meditators, for a few individual doses (0.75 mcg: one tailed $t(28) = 1.77$, $p = .05$; 1.0 mcg dose: one tailed $t(28) = 1.55$, $p = .07$), as well as when combining across the three highest doses (one tailed $t(28) = 1.83$, $p = .04$). In addition, there was a tendency for meditators to rate the onset of interoceptive changes sooner

(**Figure 26A**), and to exhibit smaller peak to peak latencies, although this difference was not statistically significant. If temporal differences in the pattern of dial ratings were the major difference, calculating the maximum cross correlation should erase the meditators' advantage. This is exactly what appeared in the data: there was no group difference in the maximum cross correlation at the individual dose level, or for the average of the three highest doses. However, since there was a small difference in the average maximum cross correlation in favor of the meditators, and since the current study used a small sample size, I conducted a power analysis to determine the sample size required to achieve a statistically meaningful result. I found that even if group sizes were increased by one order of magnitude, there would still not be a significant difference in the mean maximum cross correlation for the three highest doses (one tailed $t(298) = 1.50$, $p = .07$) (see **Table 7** for confidence intervals for differences between means). At such a sample size there would be a definite difference in the mean zero cross correlation (one tailed $t(298) = 5.99$, $p < .0001$) and mean absolute lag time (one tailed $t(298) = 4.36$, $p < .0001$) for the highest doses, indicating it is likely that the delays in onset of dial rating (and perhaps even the peak to peak latency) would be reduced for the meditators. This overall pattern of findings suggests that although meditators may notice changes in interoceptive sensations (such as the onset, offset and peak sensation) sooner than nonmeditators, it is very unlikely that this is coupled with increased accuracy in tracking the overall time course of these interoceptive sensations. The significance of such a reduced delay in rating by the meditators is unclear. It is possible that the meditators noticed the change in interoceptive sensation sooner (arguing in favor for a role of meditation in interoceptive attention). However, it is also possible that both groups noticed the change in sensation at

the same time (arguing against a role of meditation in interoceptive attention) and that meditators simply began turning the dial more quickly than the nonmeditators (suggesting perhaps that the meditators possessed greater sensorimotor coordination).

Table 7. Confidence intervals for differences between means.

	Number per group (N)	95 % Confidence interval	99% Confidence interval
Cross correlation at zero lag			
	N = 15	-.021 to .391	-.093 to .463
	N = 30	.044 to .325*	-.002 to .372
	N = 150	.125 to .245*	.107 to .264*
Maximum cross correlation			
	N = 15	-.106 to .167	-.154 to .215
	N = 30	-.062 to .123	-.092 to .153
	N = 150	-.010 to .077	-.023 to .084
Absolute lag times			
	N = 15	-22.4 to 4.7	-27.2 to 9.4
	N = 30	-18.1 to .34	-21.1 to 3.4
	N = 150	-12.9 to -4.9*	-14.1 to -3.6*

Note: Confidence intervals are for differences between the mean cross correlation of the three highest doses (meditators minus nonmeditators). Confidence intervals for the larger samples were derived by extrapolation from the mean differences observed in the current sample. *Represents a mean difference greater than or less than zero.

For the second nearly significant difference (group by dose interaction for the maximum cross correlation), examination of **Figure 18** reveals that the interaction is mainly driven by an increased cross correlation at 0.5 mcg in the nonmeditators (at this dose, $t(28) = -1.94$, $p = .06$) with a smaller contribution from an increased cross correlation at the 1.0 mcg dose in the meditators (at this dose, $t(28) = 1.3 = .20$). As **Figure 15** shows, at the 0.5 mcg dose the nonmeditators clearly generate greater dial

ratings than the meditators, although since they are greatly delayed with respect to the heart rate change, the difference in correlation only appears in the maximum cross correlation. Careful analysis of the time course at this dose reveals that this nearly significant difference could explained by increased peak heart rates in the nonmeditators over the meditators (at this dose, one tailed $t(28) = -1.88$, $p = .035$).

This overall lack of group differences in interoceptive awareness is once again surprising. Although the initial study of interoceptive awareness did not find any differences, it was subject to a number of limitations (described in detail in **Chapter 4**), all of which have been obviated by the current design. Thus the current paradigm captured appropriate changes in interoceptive awareness in all subjects tested. The current approach also incorporated a group of meditators from traditions that primarily cultivate awareness of interceptive sensations during the meditation practice.[8] These individuals were in earlier phases of their training, when a greater emphasis is placed on cultivating awareness of interoceptive sensations during the practice of meditation. Finally, the current lack of group differences in awareness appears to extend beyond heartbeat sensations to also include breathing sensations, a sensory capacity that is more commonly involved in the meditation practice.

The lack of correlation between the peak heart rate change and dial ratings in the meditators is curious, although it should be considered a premature result for a variety of reasons. First, it occurs in the context of normal cross correlations (relative to nonmeditators). The peak measure is distinct from the cross correlation measures as it

[8] A secondary analysis not reported here examined the 11 Vipassana meditators and the corresponding 11 matched nonmeditators. The same pattern of results was found, namely, significant effects of isoproterenol dose on increasing retrospective ratings, post infusion wagering and cross correlations, in the absence of any group effects or group by dose interactions whatsoever.

reflects only the maximum intensity of sensation associated with the highest dose. Although the cross correlations take into account the peak in signal, they are more heavily influenced by the temporal characteristics of the dial rating across the entire infusion period. Second, the lack of correlation could be affected by a number of factors at the individual level, resulting in outliers. For example, it appears that a more restricted range of heart rate changes were observed in the meditators as compared to the nonmeditators (e.g., no meditators experienced a peak heart rate change above 35 bpm or below 10 bpm). Alternatively, an incomplete understanding of the amplitude rating scale on the part of even a few meditators could also have resulted in reduced peak amplitudes (but normal cross correlations). Increasing the sample size in future studies would help reduce the influence of outliers, and could help determine whether the lack of correlation in the meditators is reliable.

One intriguing difference that did emerge relates to an increased variability in the perceived locations of heartbeat sensations by meditators. Nonmeditators mostly localized heartbeat sensations to the lower left side of the anterior chest, with a few individuals also perceiving heartbeat sensations in the head, abdomen and arms. Although meditators also localized heartbeat sensations to the chest, they did so more towards the midline, with added variability in the localization of heartbeat sensations to other regions such as the neck, abdomen, head, back, arms and legs. Heartbeat sensations have been localized to many of these same regions in previous studies of heartbeat detection (Jones, 1994; Jones et al., 1987; Ring and Brener, 1992), indicating that the observed variability in the present study is reliable. However, no study has described group differences in the localization of these sensations. The apparent magnitude and

systematic differences of these localizations warrant a careful consideration of the underlying causes.

Nonmeditators primarily experienced heartbeat sensations in lower left anterior chest, a region roughly corresponding to the point of maximum impulse (or PMI). The PMI is considered the location where the heart rotates, moves forward and strikes against the anterior chest wall during systole, and is a physical exam sign routinely utilized by physicians to help them determine if an individual has an enlarged heart (in which case the location of the PMI is shifted). The relative lack of localization to this region in meditators, and the diffuse localization throughout other regions, invites speculation about whether meditators might possess altered sensitivity in this body region. Several of the reported body locations more commonly reported by meditators such as the neck, belly and head share close proximity with major arteries (e.g., common carotid, abdominal aorta and external carotid arteries respectively), raising the possibility that meditators were detecting heartbeat sensations through the skin or other mechanosensitive tissues. The skin has been postulated to serve as a potential mediator of heartbeat sensations for some time, based on the knowledge that individuals with a lower body mass index are better at detecting heartbeat sensations (Rouse et al., 1988), and the fact that vibrotactile sensitivity in the finger accounts for a portion of the variance in performance on heartbeat detection (Knapp et al., 1997). In light of these findings it has even been suggested that heartbeat sensations might be mediated via Pacinian corpuscles. Although the present findings are not capable of distinguishing whether the skin or deeper structures in the viscera were mediating heartbeat sensations in the meditators and nonmeditators, it seems plausible that a combination of both could be occurring. For

example, it is possible that structures within the thoracic cavity relay heartbeat sensations localized to the chest, whereas receptors in the skin may transmit heartbeat sensations experienced in other body locations such as the belly, neck and head.

These differences in heartbeat sensation location highlight the importance of understanding the neural pathways within the body that mediate awareness of heartbeat sensations, and whether there may be differences in the mechanisms by which heartbeat sensations are transmitted in meditators and nonmeditators. Possibilities include signal transmission via sensory pathways from receptors in the heart, such as low-threshold mechanosensitive endings on vagal afferent fibers in the atria and venoatrial junction, or mechanosensitive C-fibers in the ventricles (Longhurst, 2004; Malliani, 1986). Another possibility includes intra-thoracic detection of the force generated by the heart beat on the walls of the great vessels (e.g., via baroreceptors) and in surrounding mechanosensitive thoracic tissues (Eichler and Katkin, 1994; Schandry et al., 1993). Yet another possibility includes transmission by cutaneous (dermal and epidermal) mechanosensitive fibers overlying larger arteries. Each of the aforementioned peripheral pathways project to different regions in the brainstem and cerebral cortex (e.g., insula versus primary or secondary somatosensory cortex), and thus have implications for whether heartbeat sensations should be categorized as visceral sensation, cutaneous sensation, or both.

The fact that meditators more commonly experienced heartbeat sensations in additional body locations such as the neck and abdomen leads to speculation as to whether one consequence of meditative training results in an expanded "sensory receptive field". Thus while nonmeditators appeared to more commonly utilize the PMI to detect heartbeat sensations, meditators appeared to more commonly utilize an

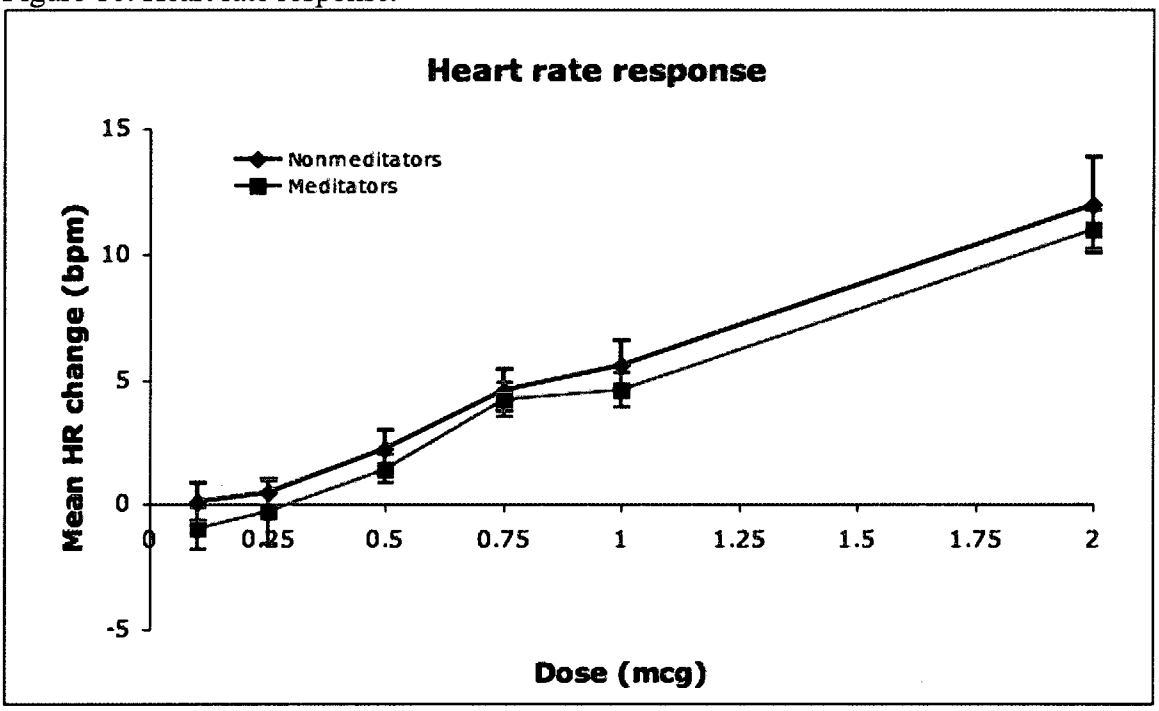
expanded range of body regions that are in close proximity of major arteries. It is possible that meditators were more commonly utilizing pulsatile sensations from the skin overlying these locations. The consequence of an expanded utilization of the skin (if indeed this were actually the case) would not appear to result in enhanced awareness of heartbeat sensations, as the current study has shown. However, it might suggest that an alternative and more promising avenue for further investigation relates to the study of skin mediated somatic sensation in meditators. Some preliminary support for this idea comes from a study that found increased tactile acuity in Tai Chi practitioners compared with a matched group of comparison subjects (Kerr, 2007). Furthermore, this notion might explain the correlation between peak heart rate and peak dial ratings in the nonmeditators and its absence in the meditators. For example, if the nonmeditators were using the PMI to sense the heartbeat, one would expect the beating of the heart against the PMI to increase with isoproterenol sensitivity, resulting in a concomitant increase in peak dial ratings. If the meditators were attending to bodily regions other than the PMI, there is no guarantee that the pulsatile forces would be transmitted equally throughout the body at increasing doses of isoproterenol (they could also, for example, be differentially influenced by postural factors). It should be noted that these comments reflect extrapolations from the observed patterns in the data, and cannot be regarded as conclusive.

Despite these mechanistic accounts, there are several alternative and perhaps more parsimonious explanations for the differences in localization of heartbeat sensations. The first relates to differences in the manner in which meditators conceptualize body processes (for example, in line with notions of diffuse and localized

forces in the body such as "energy" or "Chi" that are commonly articulated in meditation and alternative medicine traditions). The second relates to the possibility that the meditators were somehow interpreting their heartbeat sensations differently than the nonmeditators. This could occur in the context of a disproportionate preoccupation with physical symptoms, as is often observed in patients with somatization disorders. Although there is presently no evidence to support these notions, future studies could more carefully examine these possibilities by detailed psychological and psychiatric screening of meditators and nonmeditators.

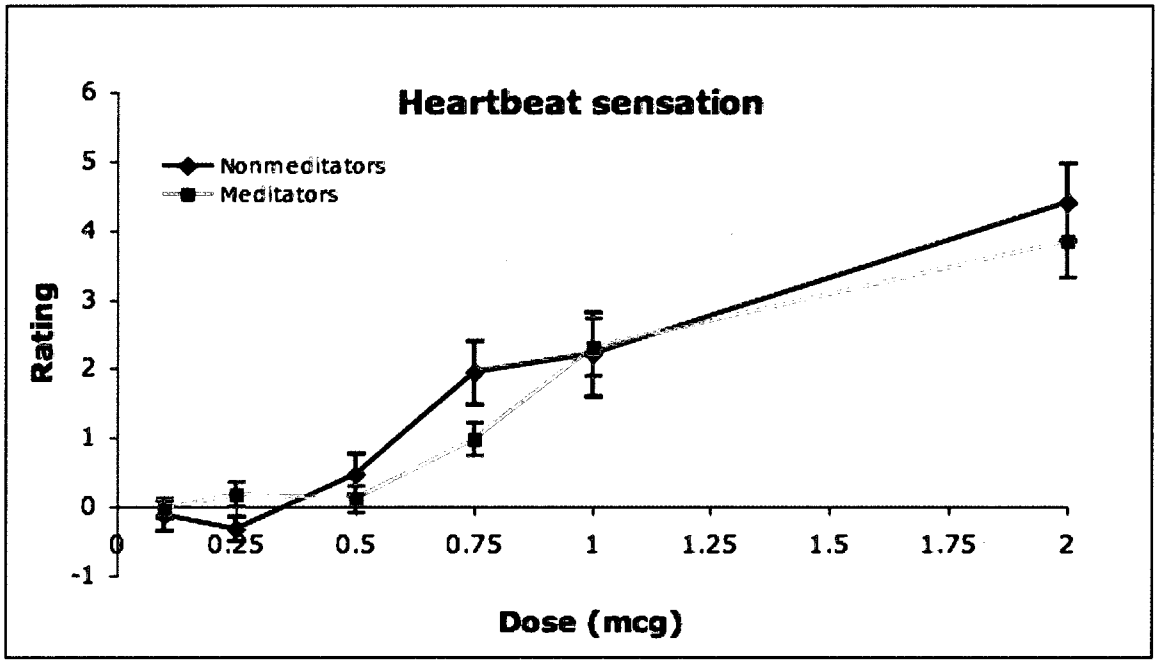
Overall, the results of this study provide strong evidence against the notion that practicing attention to internal body sensations, a core feature of meditation, enhances interoceptive awareness for a range of cardiorespiratory sensations that are commonly encountered throughout daily life.

Figure 10. Heart rate response.



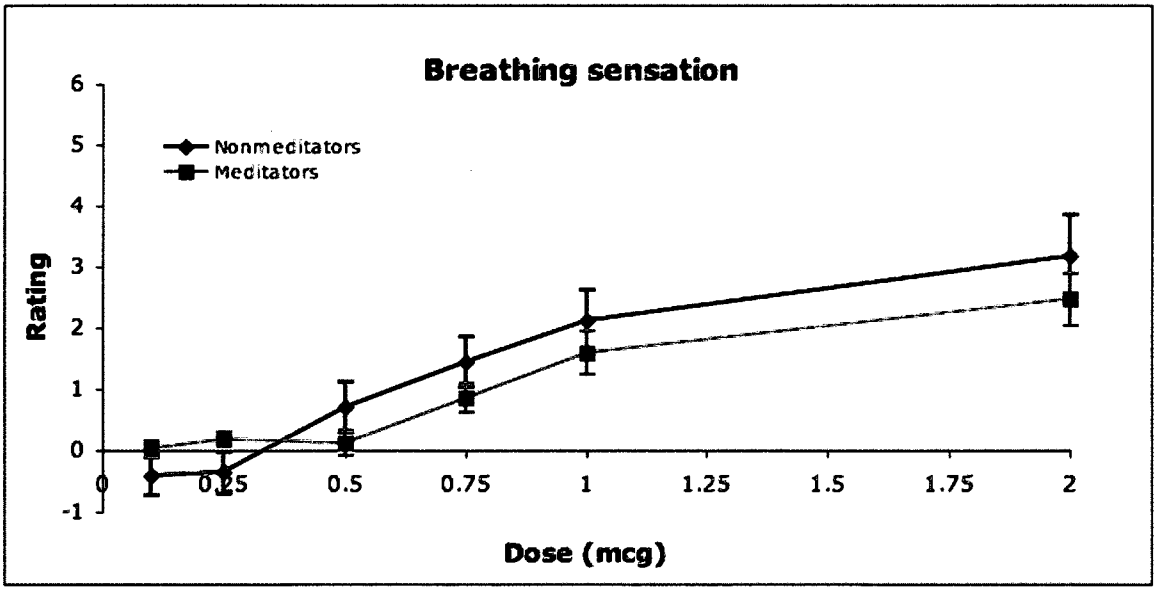
Means +/- SE.

Figure 11. Retrospective intensity of heartbeat sensations in meditators and nonmeditators.



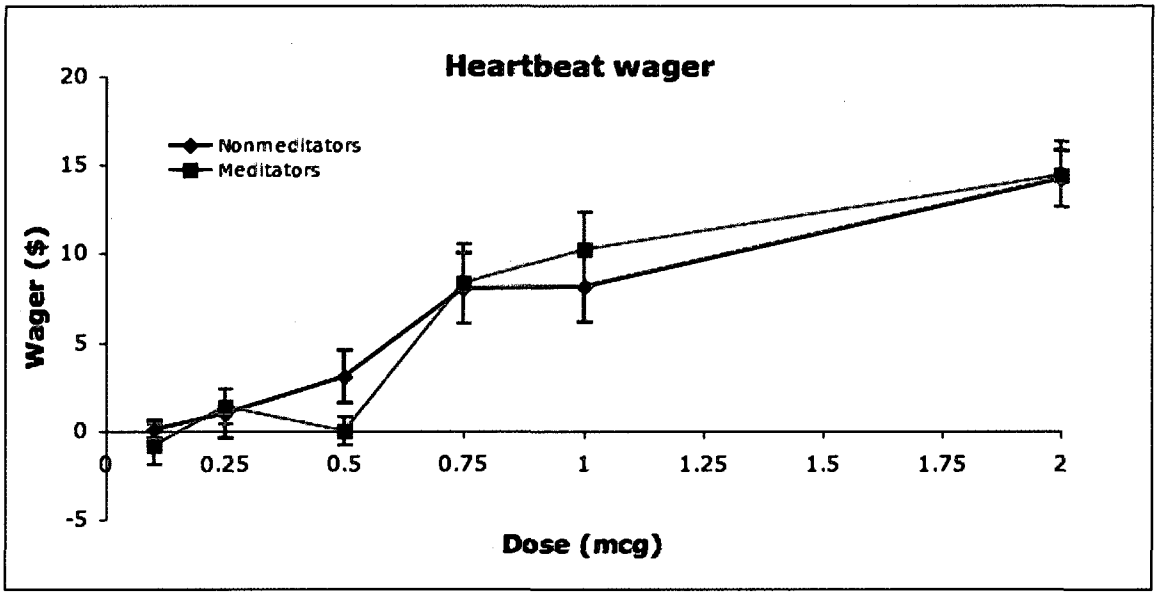
Means +/- SE.

Figure 12. Retrospective intensity of breathing sensations in meditators and nonmeditators.



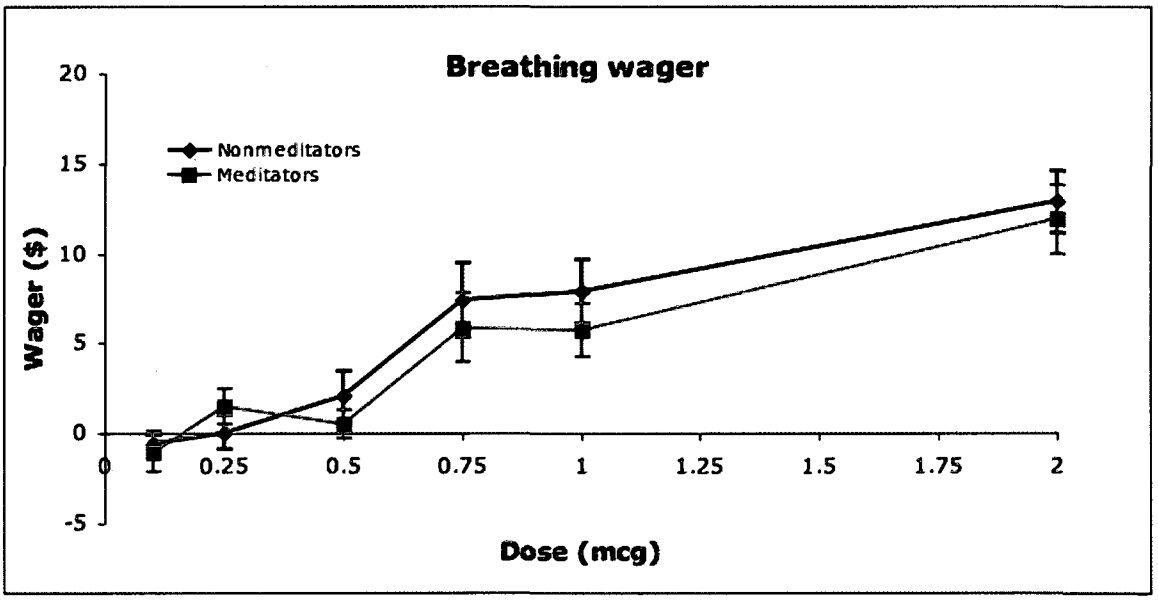
Means +/- SE.

Figure 13. Post infusion wagering on the presence of heartbeat change in meditators and nonmeditators.



Means +/- SE.

Figure 14. Post infusion wagering on the presence of breathing change in meditators and nonmeditators.



Means +/- SE.

Figure 15. Mean time course of heart rate and interoceptive dial ratings for lower doses.

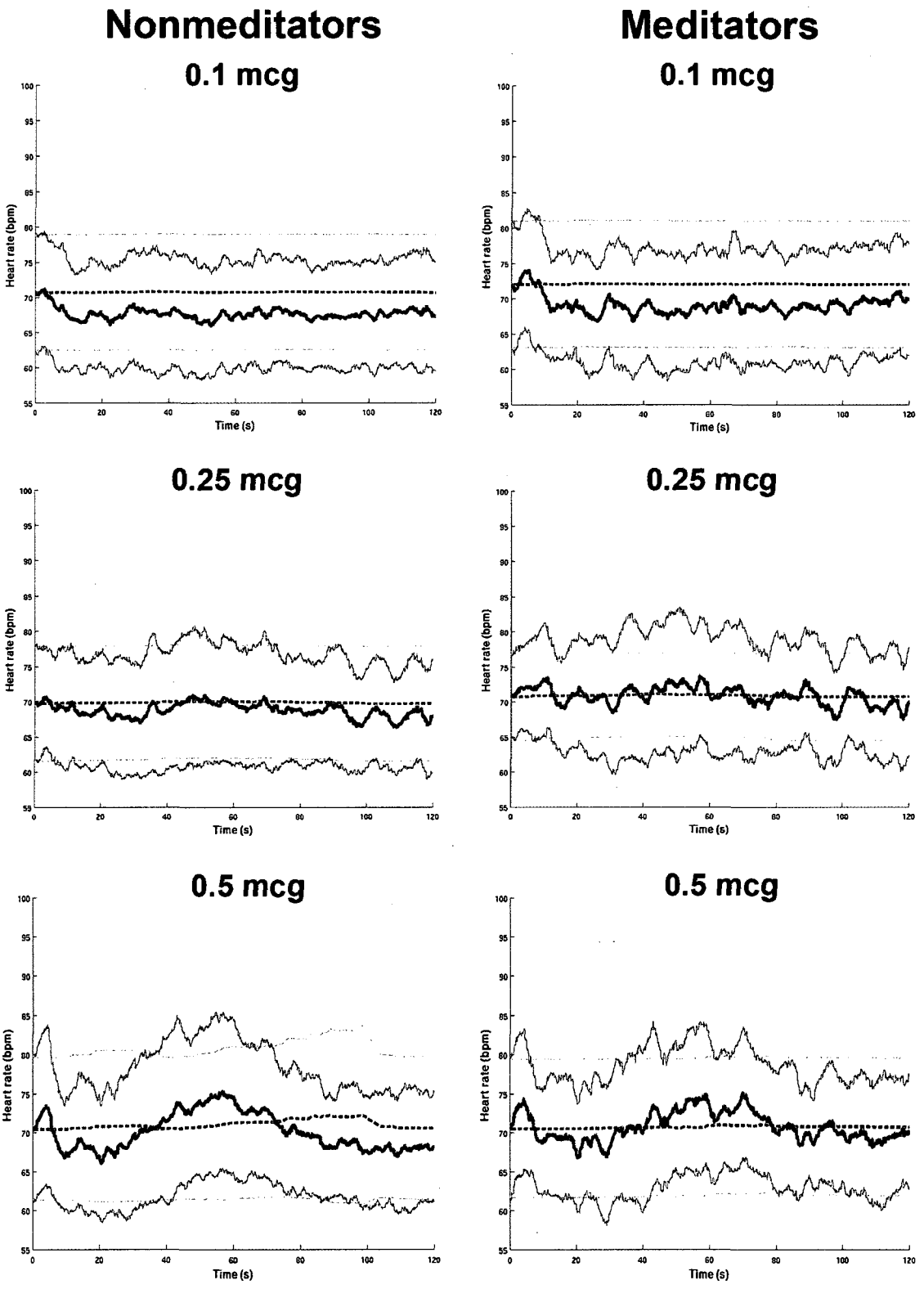


Figure 15—continued. Note: Heart rate at each dose (thick black line) and associated normalized dial rating (thick dashed gray line) for each group. Thin lines indicate SE.

Figure 16. Mean time course of heart rate and interoceptive dial ratings for higher doses.

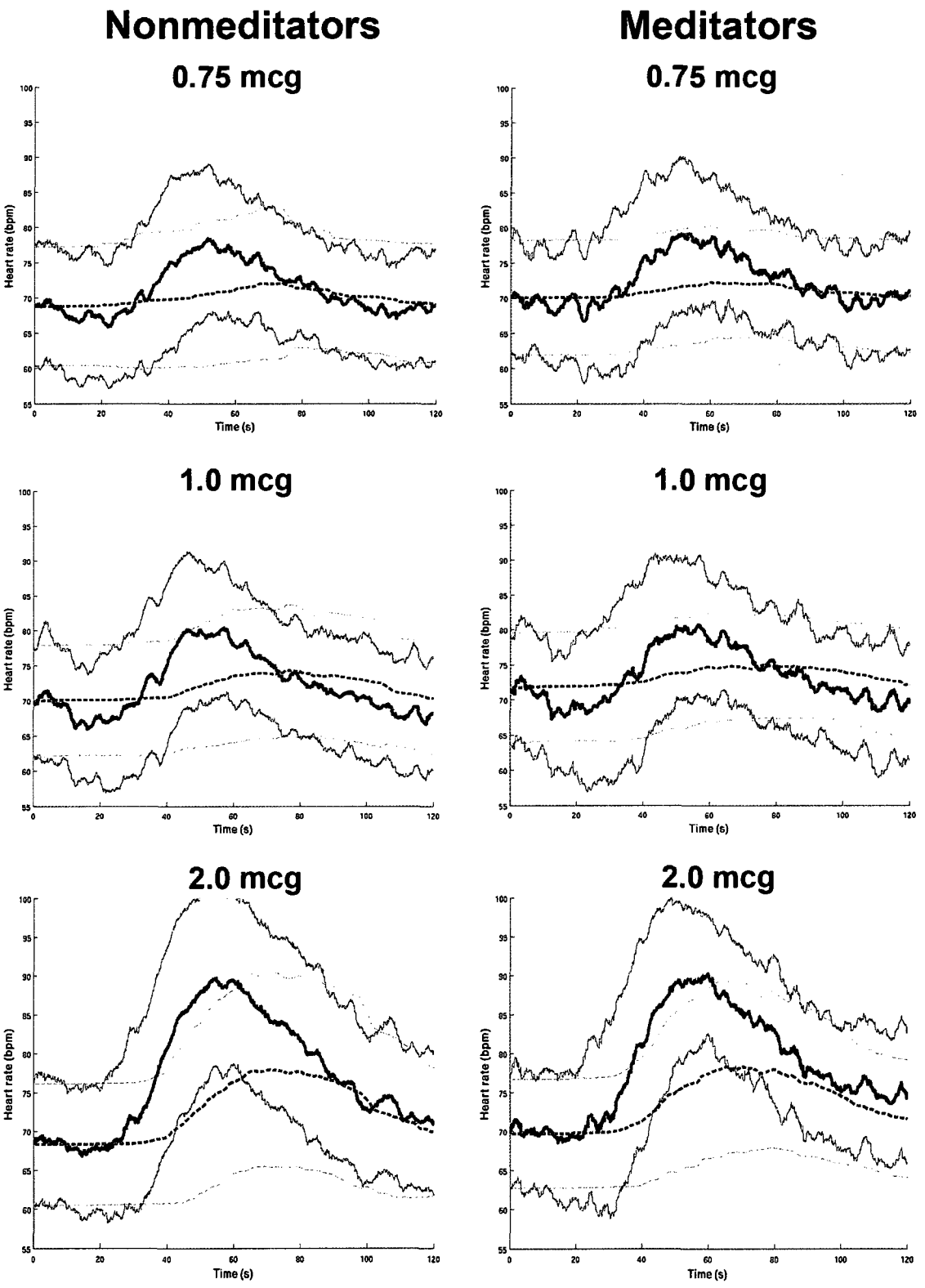
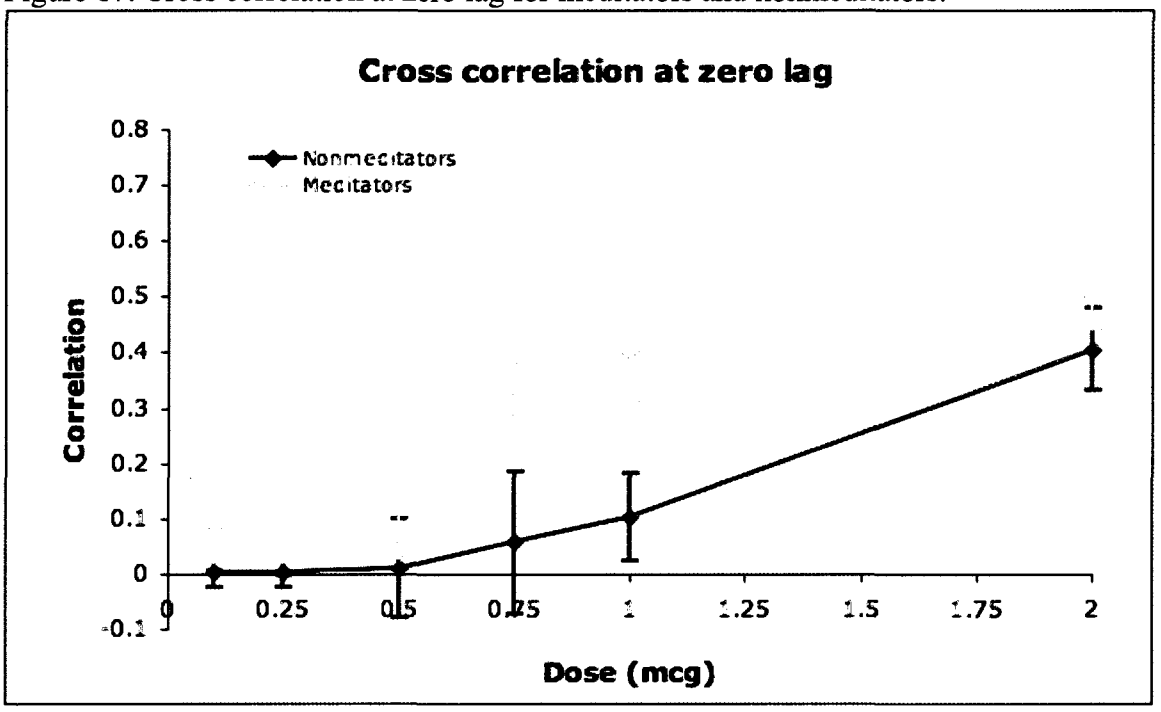


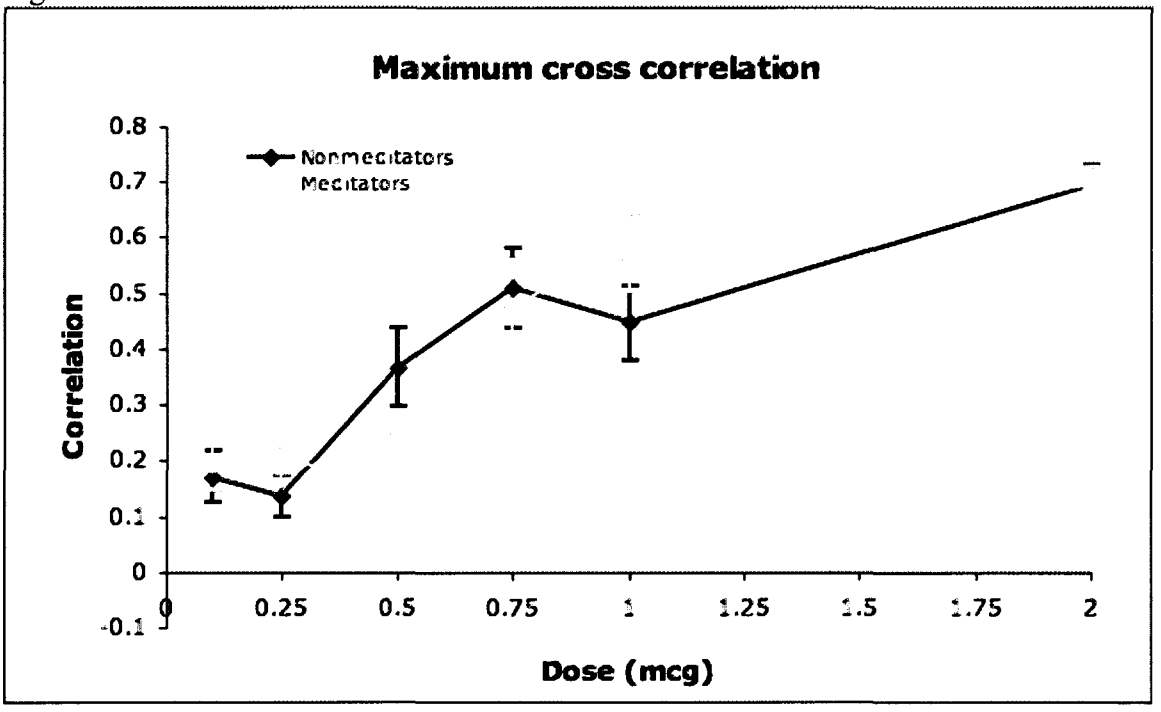
Figure 16—continued. Note: Heart rate at each dose (thick black line) and associated normalized dial rating (thick dashed gray line) for each group. Thin lines indicate SE.

Figure 17. Cross correlation at zero lag for meditators and nonmeditators.



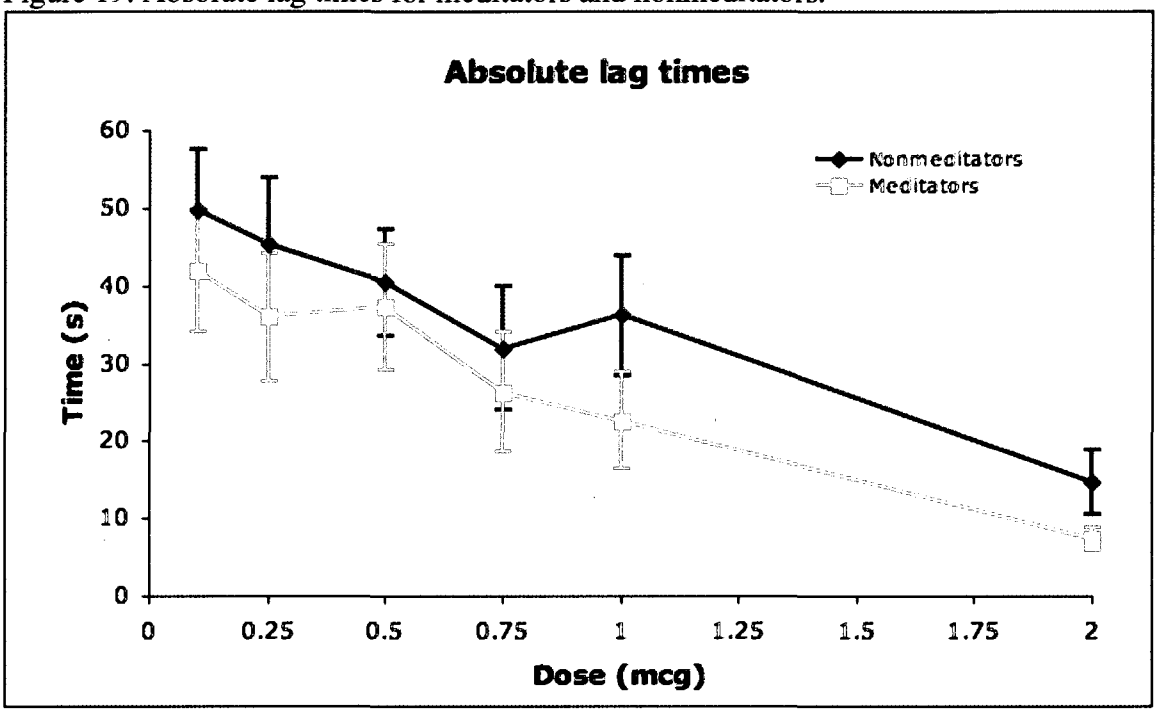
Means +/- SE.

Figure 18. Maximum cross correlation for meditators and nonmeditators.



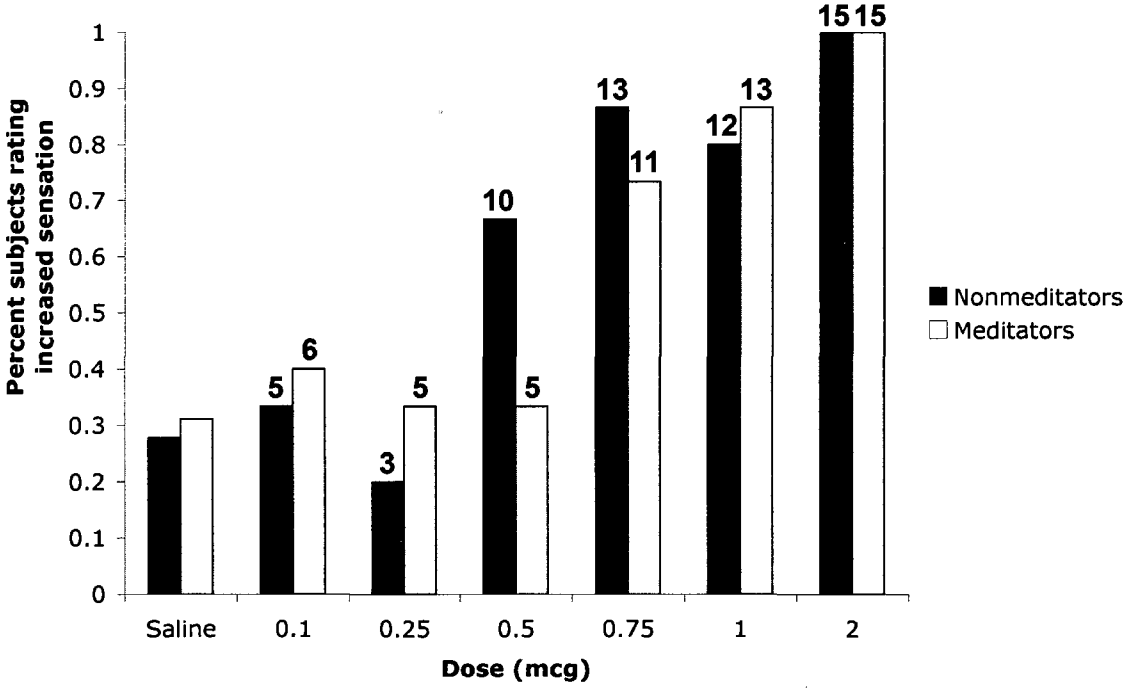
Means +/- SE.

Figure 19. Absolute lag times for meditators and nonmeditators.



Means +/- SE.

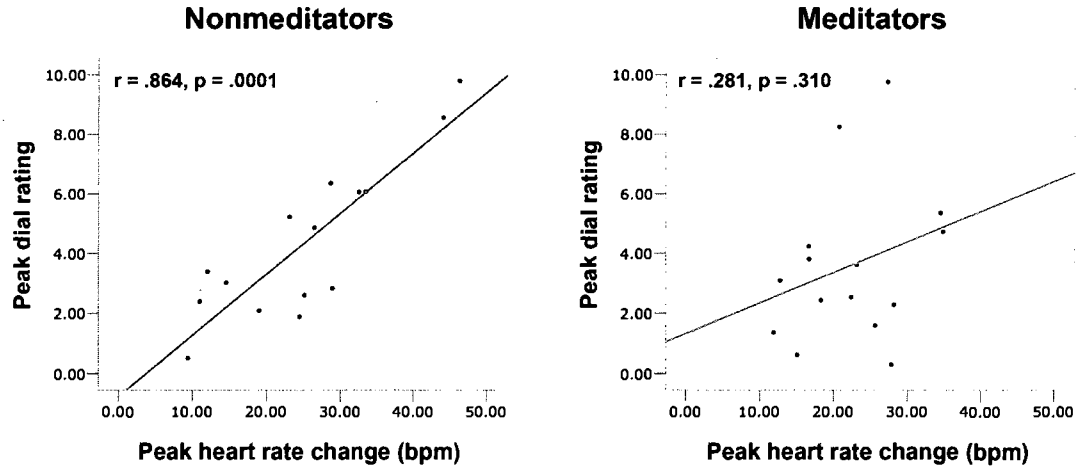
Figure 20. Frequency of participants reporting increases in interoceptive sensations.



A participant was considered to have endorsed an increase in sensation above baseline if

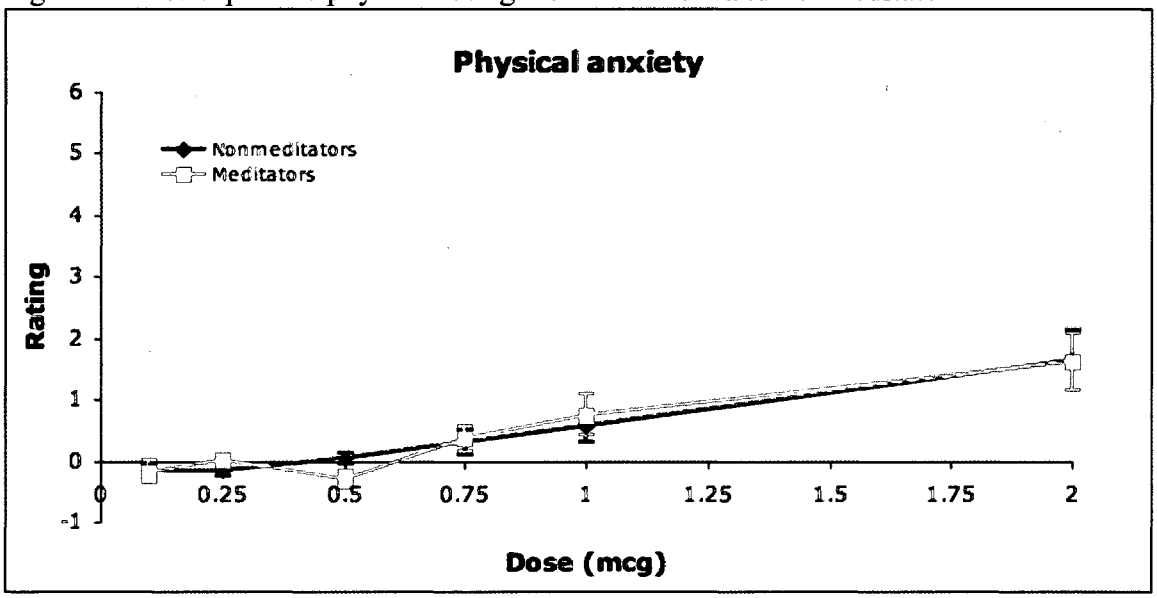
Figure 20—continued. they turned the dial above zero at any point during the 90 second infusion period. The numbers at the top of the bars denote the number of participants endorsing increased sensation at each dose.

Figure 21. Peak intensity rating versus peak heart rate change at the highest dose.



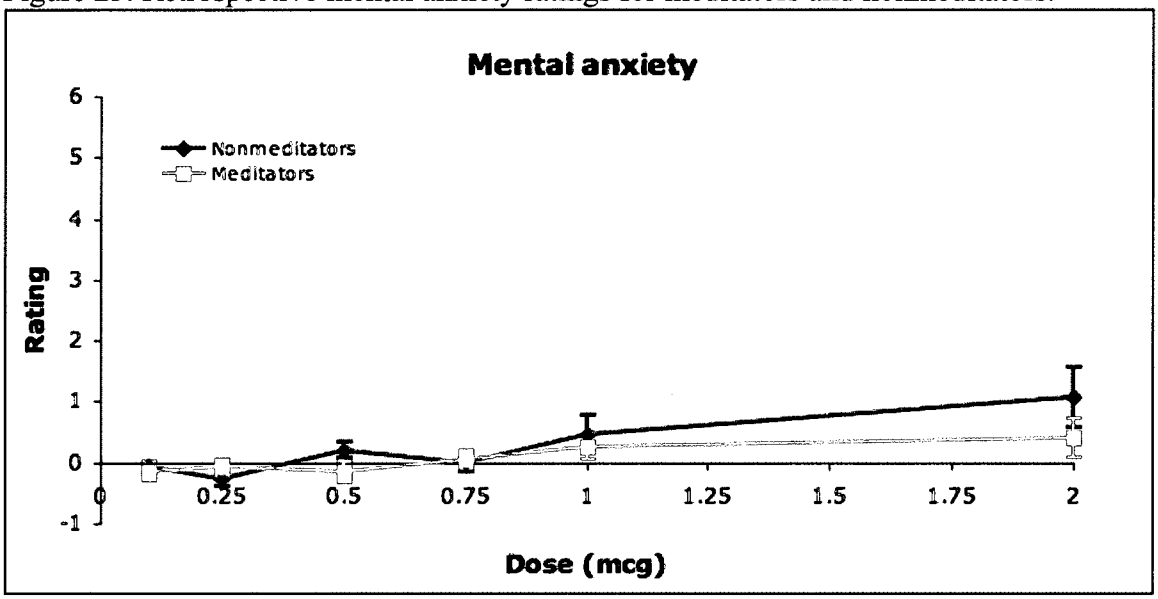
Dial rating scale: 0 = 'normal' to 10 = 'most ever'.

Figure 22. Retrospective physical ratings for meditators and nonmeditators.



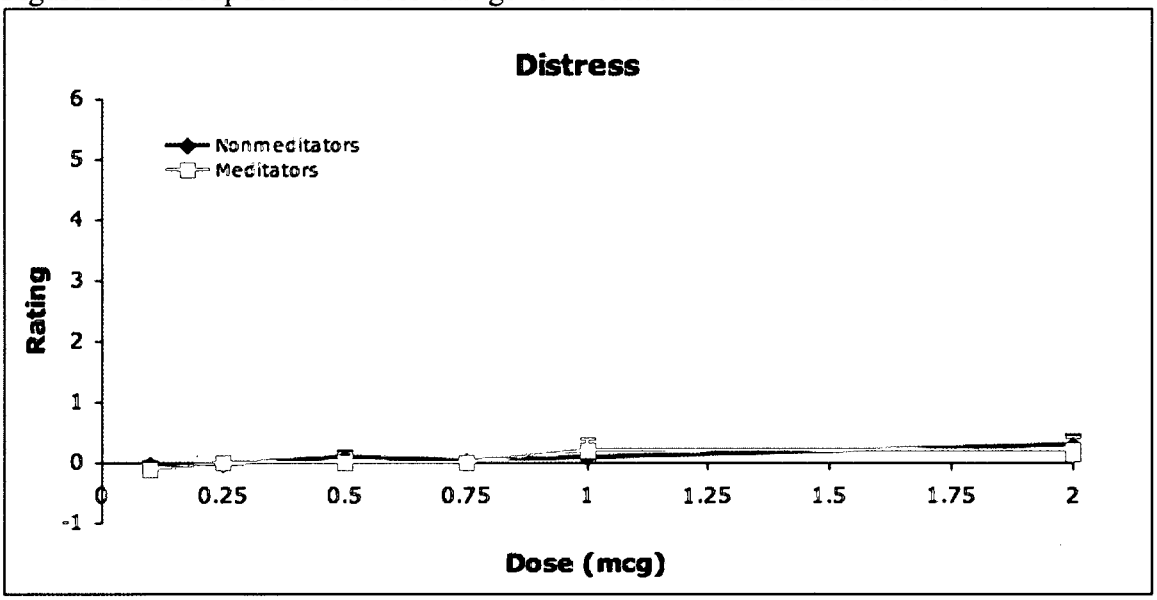
Means +/- SE.

Figure 23. Retrospective mental anxiety ratings for meditators and nonmeditators.



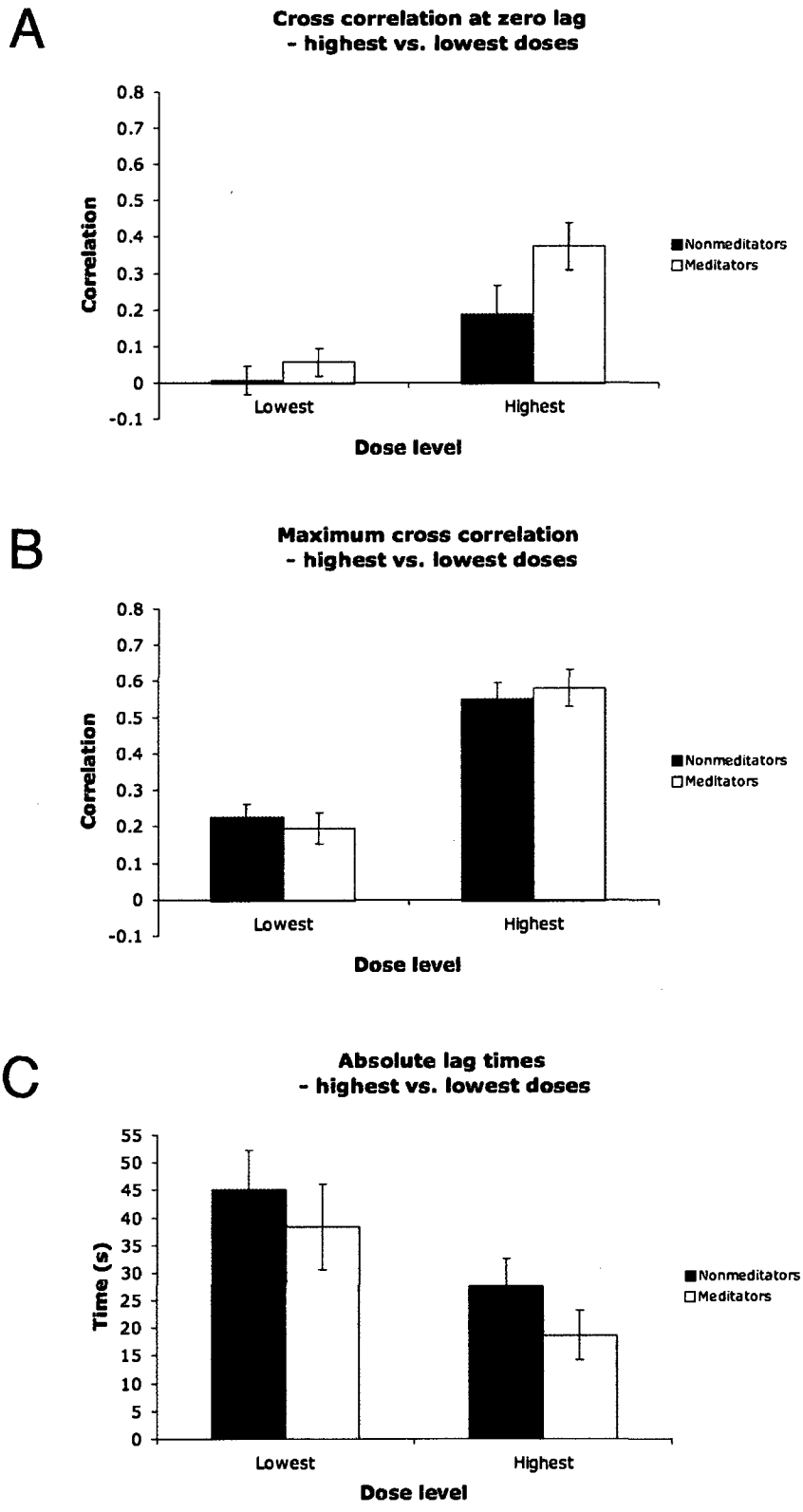
Means +/- SE.

Figure 24. Retrospective distress ratings for meditators and nonmeditators.



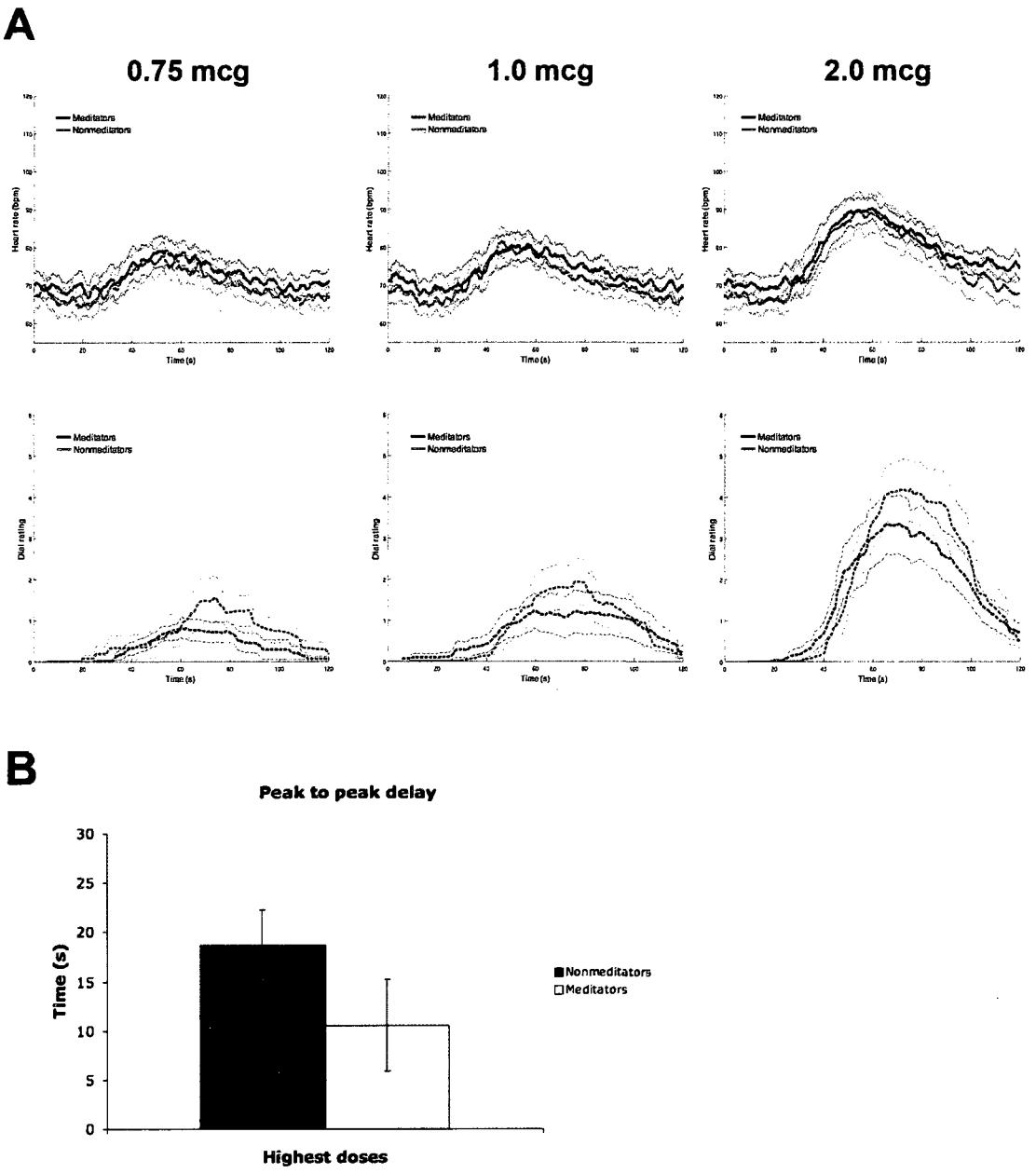
Means +/- SE.

Figure 25. Average cross correlations: lowest vs. highest doses.



Means +/- S.E.

Figure 26. Time series analysis of dial ratings at the highest doses.



(A) Mean time course for heart rate and raw (nonnormalized) dial ratings for the three highest doses. (B) Average peak to peak delay for the three highest doses (peak dial rating minus peak heart rate change). Thick lines indicate means, thin lines indicate SE.

Figure 27. Locations of heartbeat sensations for meditators and nonmeditators.

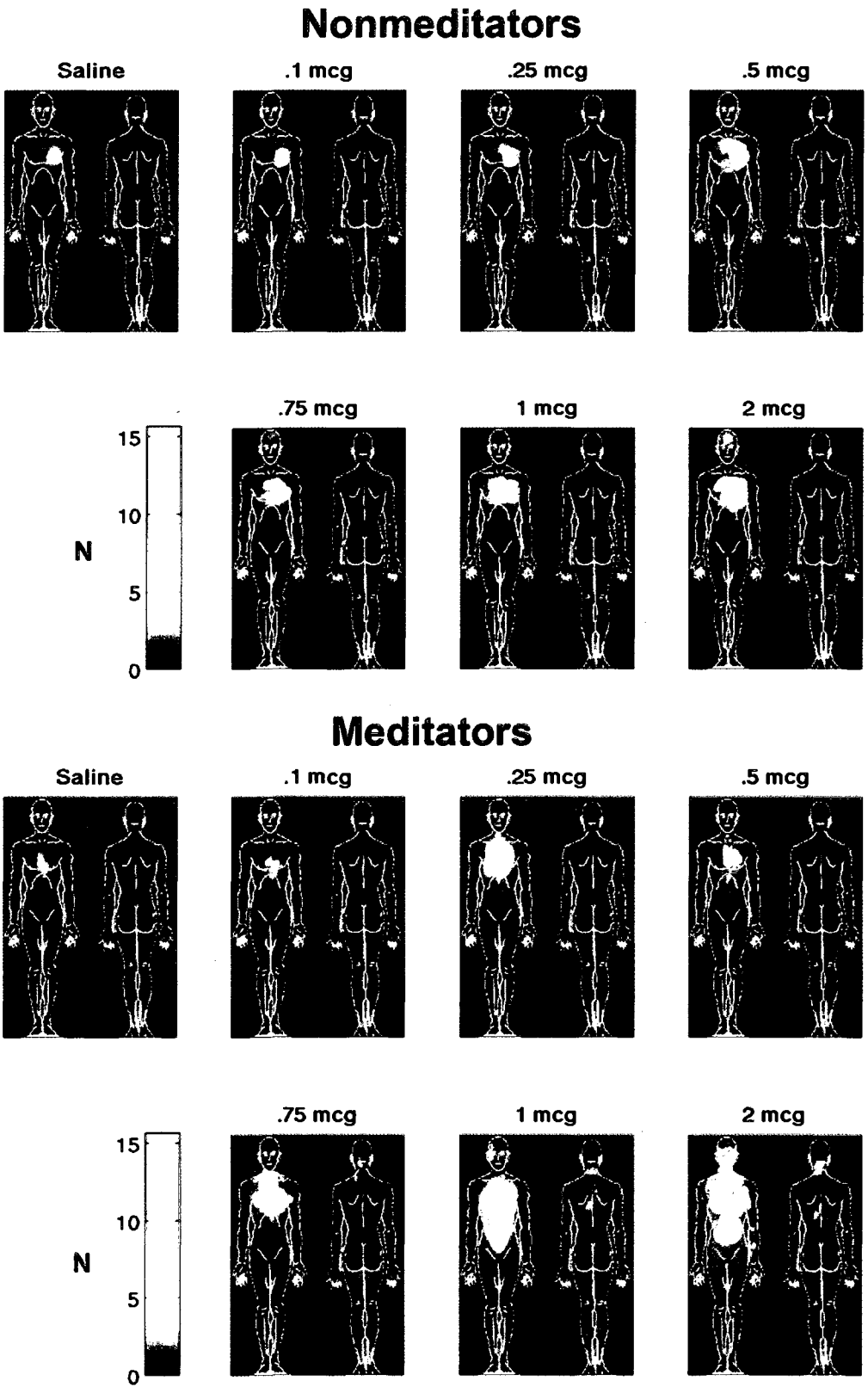
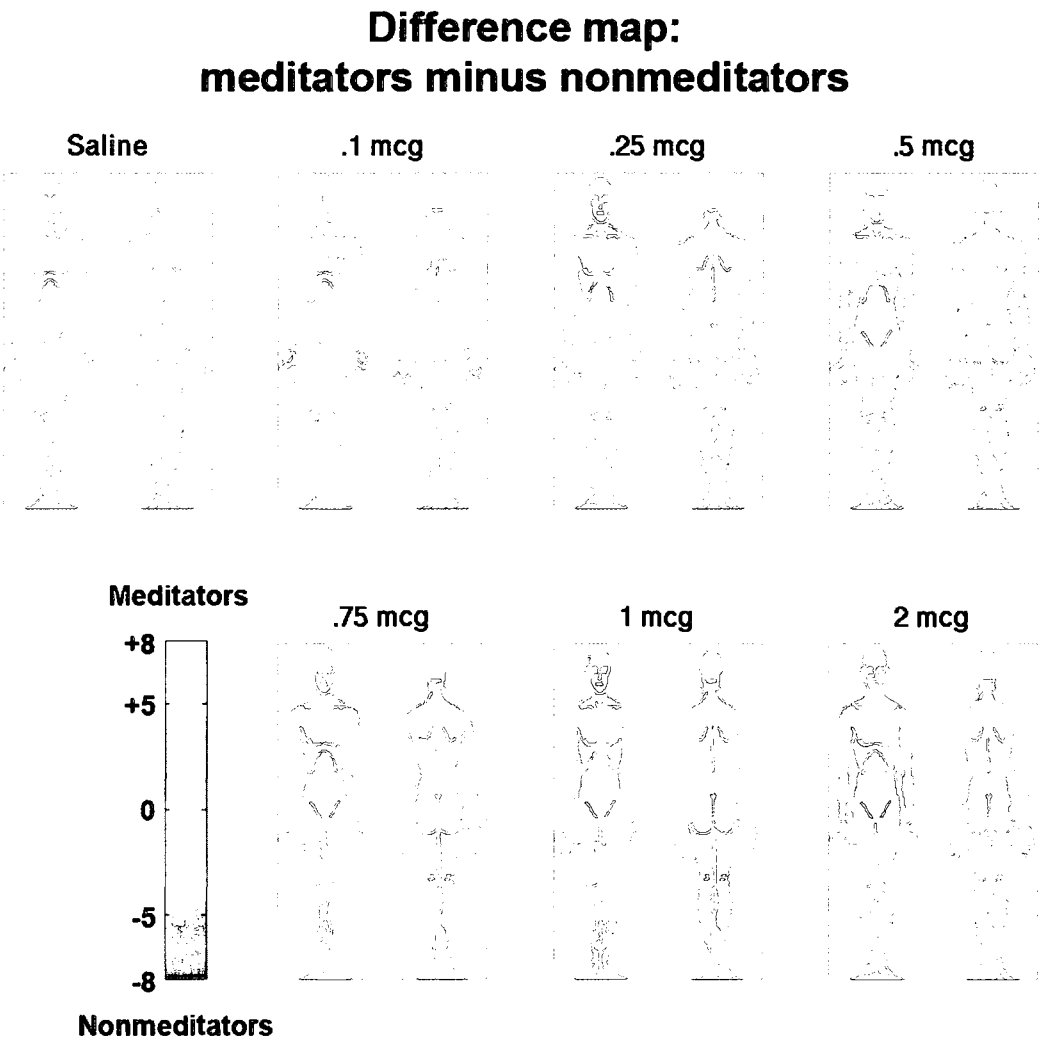


Figure 27—continued. Note: For each group all 15 participants' traced outlines of heartbeat sensations are overlapped for each dose, as well as for saline. Hotter colors correspond to a greater number of overlaps across participants.

Figure 28. Difference map of locations of heartbeat sensations: meditators versus nonmeditators.



Note: Hotter colors correspond to a greater numbers of meditators perceiving the heartbeat sensation in a given body location relative to nonmeditators. Colder colors correspond to greater numbers of nonmeditators perceiving the heartbeat sensation in a given body location relative to meditators.

CHAPTER 7. THE EFFECT OF MEDITATION ON REGULATION OF INTERNAL BODY STATES

7.1 Background

The degree to which meditation results in physiologically quiescent states is unknown. A recent study suggested a novel effect of meditation on the ability to regulate increased levels of cardiovascular arousal. (Dimsdale and Mills, 2002) reported a case study in which a female meditator was spontaneously able to counteract the chronotropic effects of isoproterenol at 1. 0, 2.0 and 4.0 mcg doses during a meditation period (**Figure 2**). Such decreases were not observed in the same participant during a repeat visit with an instruction not to meditate, suggesting that this individual possessed the capacity regulate cardiac arousal through her meditation practice.

Although this case study tantalizingly hints that the practice of meditation may reduce the cardiovascular response to acute physiological stress, it raises more questions than it answers. First, since the electrocardiographic measure relied on an intermittent readout taken 60 seconds after each infusion, it is possible that the peak heart rate responses did not occur during time point for this meditator on the particular session of interest, and therefore that the finding was spurious. As a consequence, the investigators recommended follow up studies that incorporated continuous measures of heart rate. Second, the meditator was not formally trained, and indicated that she would often enter such deep states that she would need to set an alarm clock to rouse her from meditation. Thus it is possible that this individual likened sleep (or some other altered state of consciousness) with meditation, and that the observed effect had nothing to do with meditation. Finally, assuming this phenomenon were real, it raises questions about the

potential physiological mechanisms that could instantiate such an effect. In light of these limitations, I performed a group level study to investigate the response to isoproterenol in formally trained meditators during meditation and during rest. I also studied a group of nonmeditators during a relaxation condition and during rest, to determine whether the effect was specific to the meditation practice or could be elicited by individuals consciously trying to regulate their level of physiological arousal.

Based on the hypothesis that the long term practice of meditation is associated with an enhanced ability to regulate body states in the face of acute physiological arousal, I predicted that in the face of isoproterenol infusions, during the meditation practice meditators would display lower heart rate increases than nonmeditators during a relaxation practice. I also predicted that such heart rate reductions in the meditators would be specific to meditation, i.e., that meditators and nonmeditators would have equivalent heart rate responses to isoproterenol at rest.

7.2 Method

7.2.1 Participants

15 nonmeditators and 15 meditators participated in the study. Each nonmeditator was individually matched to a corresponding meditator based on three criteria: age, gender and body mass index. The participants included in the current study are the same as those included in the prior study, and hence met the same inclusion criteria as previously described (see **Table 6** for complete demographics).

7.2.2 Tasks

Participants were informed that they would be asked to rest quietly with their eyes open on two occasions, and to meditate (or alternatively, to relax) with their eyes closed on two occasions. Meditators were instructed to engage in their usual meditation practice for a period of 15 to 20 minutes during the meditation condition.[9] Nonmeditators were instructed in the performance of a cognitive relaxation strategy for a period of 15 to 20 minutes during the relaxation condition. In particular, nonmeditators were asked to engage in a relaxation practice they had found useful for themselves in the past, one that would help them to "relax your mind and body, one that will help you slow your thoughts, slow your breathing, and slow your heart rate." If a nonmeditator reported no such a strategy, they were given the option to perform one or any combination of several relaxation strategies including (1) reliving a pleasant memory, such as a warm day at the beach, (2) replaying their favorite song internally, (3) completely relaxing their musculature and (4) slowing their breathing. These strategies were selected with the aim of facilitating elicitation of the relaxation response. Nonmeditators were specifically instructed to avoid falling asleep during the relaxation practice, despite any inclinations that might arise. During the rest conditions both groups were instructed to avoid engaging in their meditation/relaxation practice, and instead, to explore their everyday thoughts (for example, thoughts about activities from the recent past such as what they had done the day before, or thoughts about potential future activities such as what they would do once the study had been concluded).

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[9] Note: since the Kundalini tradition offers many different types of meditations that are purported to derive different types of effects, Kundalini meditators were specifically instructed to select a specific meditation practice that they had found helped them lower their level of bodily arousal in the past. Since the Vipassana tradition does not provide such an approach, Vipassana meditators were simply instructed to engage in their usual meditation practice.

All participants were informed that they would be receiving isoproterenol or saline at some points during the entire session, but that neither they nor the experimenter would know when the nurse administered a particular agent. The room in which the study took place was kept quiet and was dimly lit throughout duration of the study.

7.2.3 Infusion protocol

Two sets of standard isoproterenol infusion protocols and two sets of matched saline infusion protocols were administered. The isoproterenol protocols consisted of sequentially increasing isoproterenol doses of 0.1, 0.5, 1.0, 2.0 and 4.0 (mcg), delivered 3.5 minutes apart.[10] The saline protocols consisted of five identically delivered bolus infusions of saline.

7.2.4 Infusion delivery

Each infusion (isoproterenol and saline) consisted of two 3 milliliter (ml) bolus infusions delivered sequentially through an intravenous catheter. During isoproterenol infusions, a 3 ml bolus containing the specified dose was delivered, immediately followed by a 3 ml bolus of saline to flush the line. During saline infusions, a 3 ml bolus of saline was delivered, immediately followed by an additional 3 ml bolus of saline. Both bolus volumes were administered in entirety within a 15 second period by a nurse from the General Clinical Research Center. This method of delivery minimized the participant's ability to use external cues to distinguish between the different infusion types, and ensured rapid and standardized systemic introduction of isoproterenol.

[10] The isoproterenol sensitivity tests listed here are identical to those mentioned in Chapter 5. Therefore, the regulation experiment preceded the interoceptive awareness experiment equally in all participants. The reversed order of presentation has been chosen to facilitate the conceptual integration of this work.

7.2.5 Procedure

The infusion protocol order was pseudorandomized and single blinded. This was necessitated by practical considerations: in order to ensure the safety of isoproterenol administration, a physician was required to be present during the first round of infusions. Due to constraints in the physician's schedule, a majority of the time the first condition consisted of isoproterenol infusions. However, the remaining task selection process (for example, isoproterenol plus rest versus isoproterenol plus meditation) remained randomized, and was determined by the nurse administering the infusions. The remaining three infusion conditions were completely randomized.

7.2.6 Psychophysiological measures

The measures of heart rate were identical to those employed in the previous studies. Thus heart rate was continuously sampled (at a rate of 200 Hz) throughout all infusions. All artifacts affecting the cardiac waveform (e.g., movement related and cardiac, such as premature ventricular contractions) were visually identified and manually removed.

Several measures of heart rate were derived from the instantaneous cardiac waveform. These measures were divided across three epochs of specific relevance to the timeline of heart rate changes induced by isoproterenol (**Figure 29**). The first epoch consisted of a 30 second interval starting immediately after the onset of each infusion. This reflects a period when isoproterenol induced heart rate changes have yet to occur. The second epoch consisted of a 90 second interval beginning 30 seconds after infusion administration. This reflects a period when isoproterenol induced heart rate changes are most likely to occur. The third epoch consisted of a 60 second period beginning

immediately after the end of the second epoch. This interval reflects a period when the heart rate is still returning back to baseline, or has already done so. These three epochs combine to represent the 3 minutes following each infusion onset, when the probability of isoproterenol induced changes in heart rate are maximal. Because the participant could hear the nurse was preparing the next infusion during the final 30 second period (of the 3.5 minutes separating each infusion), this period was not included in the analysis to remove any potential influence of this preparatory period on the heart rate.

Within each epoch, four measures were obtained. (1) Mean heart rate change. This was determined for each participant by subtracting the average heart rate during epoch 1 from epoch 2. This controls for elevations in baseline heart rate that might occur following increasing doses, and provided a reliable estimate of changes induced by isoproterenol administration. (2) Mean heart rates for each participant were determined across epochs 1, 2 and 3. This provided a measure of heart rate over each period of interest in units similar to those reported by Dimsdale & Mills (2002). (3) The lowest heart rates occurring for each participant within a 3 second period throughout epochs 1, 2 and 3. This provided a measure of the floor effect in the heart rate response to isoproterenol. Since Dimsdale and Mills (2002) relied upon an automated measure of heart rate (which provides only a momentary measure of heart rate), it is possible that the heart rate responses they observed reflected local minima occurring during a brief span of time. This three second window was selected in order to identify whether similarly low levels of heart rate response would corroborate this possibility. (4) The highest heart rates occurring for each participant within a 3 second period were identified across

epochs 1, 2 and 3. This provided a measure of the ceiling effect of the heart rate response to isoproterenol.

Finally, heart rate and blood pressure were measured with an automated noninvasive blood pressure monitoring device (inflatable cuff wrapped around the dominant arm) similar to what was likely used during the Dimsdale & Mills (2002) study.[11] These latter measures were initiated 30 seconds after the start of each infusion, in an effort to mimic the type of measurement used by Dimsdale & Mill (2002). Due to variability in the amount of time taken for the machine to generate a blood pressure reading, each measure with this device was obtained approximately 60 to 80 seconds after each infusion onset (maximum range observed: 58 to 93 seconds after initiating measurement).

7.2.7 Data analysis

2 x 4 x 5 repeated measures ANOVAs were performed on each univariate dependent variable of interest, with group (meditators, nonmeditators) as the between subjects factor and with condition (isoproterenol plus meditation/relaxation, isoproterenol plus rest, saline plus meditation/relaxation, saline plus rest) and dose (isoproterenol, saline) as the within subjects factors. All univariate repeated measures ANOVA tests were assessed for violations of the sphericity assumption, and when violated, were corrected with the Huynh-Feldt method. In these instances the corrected p values are reported, along with the Huynh-Feldt epsilon (ε) correction.

[11] These measures were incorporated after several participants had been tested. As a result, data for the full sample are unavailable (measures were collected from 11 meditators and 13 nonmeditators).

7.3 Results

7.3.1 Mean heart rate change

As expected, a 2 x 4 x 5 repeated measures ANOVA revealed a significant effect of condition $F(1, 3) = 140.22$, $p < .0001$, $\eta_p^2 = .83$, $\varepsilon = .780$, and dose $F(1, 4) = 68.5$, $p < .0001$, $\eta_p^2 = .71$, $\varepsilon = .554$, on the mean heart rate response to isoproterenol. There was a significant interaction between condition and dose $F(1, 12) = 68.54$, $p < .0001$, $\eta_p^2 = .59$, $\varepsilon = .737$, suggesting that increases in heart rate occurred at increasing doses of isoproterenol (but not saline) administration. However, despite these changes, there were no group differences in the heart rate response to isoproterenol. There was no effect of group $F(1, 28) = 2.97$, $p = .10$, $\eta_p^2 = .10$, and there were no interactions between condition and group $F(1, 3) = .21$, $p = .84$, $\eta_p^2 = .01$, between dose and group $F(1, 4) = .21$, $p = .84$, $\eta_p^2 = .01$, or between condition and group and dose $F(1, 12) = .82$, $p = .60$, $\eta_p^2 = .03$, suggesting that the heart rate increases induced by isoproterenol were equivalent for both groups (**Figure 30A**).

7.3.2. Mean heart rate

Epoch 1. A 2 x 4 x 5 repeated measures ANOVA did not find an effect of condition $F(1, 3) = .39$, $p = .76$, $\eta_p^2 = .01$, but did reveal a significant effect of dose $F(1, 4) = 4.74$, $p = .008$, $\eta_p^2 = .15$, $\varepsilon = .616$, on the mean heart rate during epoch 1. There was also a significant interaction between condition and dose $F(1, 12) = 4.41$, $p < .0001$, $\eta_p^2 = .14$, $\varepsilon = .772$, suggesting that increases in mean heart rate during epoch 1 occurred at increasing doses of isoproterenol (but not saline) administration. However, despite these changes, there were no group differences in heart rate during this period. There was no effect of group $F(1, 28) = 1.20$, $p = .28$, $\eta_p^2 = .04$, and there were no interactions between

condition and group $F(1, 3) = 2.00$, $p = .12$, $\eta_p^2 = .07$, between dose and group $F(1, 4) = .33$, $p = .76$, $\eta_p^2 = .01$, or between condition and group and dose $F(1, 12) = .74$, $p = .68$, $\eta_p^2 = .03$, suggesting that the mean heart rate increases observed for increasing doses of isoproterenol during epoch 1 occurred equivalently for both groups. This pattern of findings reflects that fact that some of the heart rate changes induced by isoproterenol (particularly at the higher doses) began occurring early, as was observed in several participants.

Epoch 2. A 2 x 4 x 5 repeated measures ANOVA revealed a significant effect of condition $F(1, 3) = 84.19$, $p < .0001$, $\eta_p^2 = .75$, and dose $F(1, 4) = 84.19$, $p < .0001$, $\eta_p^2 = .75$, $\varepsilon = .402$, on the mean heart rate during epoch 2. There was also a significant interaction between condition and dose $F(1, 12) = 72.91$, $p < .0001$, $\eta_p^2 = .72$, $\varepsilon = .330$, suggesting that increases in mean heart rate during epoch 2 occurred at increasing doses of isoproterenol (but not saline) administration. However, despite these changes, there were again no group differences in heart rate during this period. There was no effect of group $F(1, 28) = .65$, $p = .43$, $\eta_p^2 = .02$, and there were no interactions between condition and group $F(1, 3) = 2.00$, $p = .12$, $\eta_p^2 = .07$, between dose and group $F(1, 4) = 1.44$, $p = .24$, $\eta_p^2 = .05$, or between condition and group and dose $F(1, 12) = .70$, $p = .59$, $\eta_p^2 = .02$, suggesting that the mean heart rate increases observed for increasing doses of isoproterenol during epoch 2 occurred equivalently for both groups (**Figure 30B**).

Epoch 3. A 2 x 4 x 5 repeated measures ANOVA revealed a significant effect of condition $F(1, 3) = 8.30$, $p < .0001$, $\eta_p^2 = .23$, and dose $F(1, 4) = 30.66$, $p < .0001$, $\eta_p^2 = .52$, $\varepsilon = .440$, on the mean heart rate during epoch 2. There was also a significant interaction between condition and dose $F(1, 12) = 20.72$, $p < .0001$, $\eta_p^2 = .43$, $\varepsilon = .418$,

suggesting that increases in mean heart rate during epoch 3 occurred at increasing doses of isoproterenol (but not saline) administration. However, despite these changes, there were again no group differences in heart rate during this period. Once again, there was no effect of group $F(1, 28) = .92$, $p = .35$, $\eta_p^2 = .03$, and there were no interactions between condition and group $F(1, 3) = 1.68$, $p = .18$, $\eta_p^2 = .06$, between dose and group $F(1, 4) = .93$, $p = .39$, $\eta_p^2 = .03$, or between condition and group and dose $F(1, 12) = .65$, $p = .67$, $\eta_p^2 = .02$, suggesting that the mean heart rate increases observed for increasing doses of isoproterenol during epoch 3 occurred equivalently for both groups. This pattern of findings reflects that fact that some of the heart rate changes induced by isoproterenol (particularly at the higher doses) were still present and in the process of returning to baseline, as was observed in several participants.

7.3.3. Highest and lowest heart rates

The basic pattern of findings reported above also held true for the highest and lowest heart rates observed during epochs 1, 2 and 3. Specifically, increases in the highest (and lowest) heart rates occurred for conditions containing increasing doses of isoproterenol (but not saline), in the absence of any group differences whatsoever. In the interest of brevity these statistics have not been reported here, but rather, the reader is referred to **Figure 31.**

7.3.4. Automated heart rate and blood pressure

Automated heart rate. A 2 x 4 x 5 repeated measures ANOVA revealed a significant effect of condition $F(1, 3) = 115.88$, $p < .0001$, $\eta_p^2 = .84$, $\varepsilon = .813$, and dose $F(1, 4) = 74.42$, $p < .0001$, $\eta_p^2 = .77$, $\varepsilon = .909$, on the automated measure of heart rate. There was also a significant interaction between condition and dose $F(1, 12) = 40.31$, $p <$

.0001, $\eta_p^2 = .65$, $\varepsilon = .438$, suggesting that increases in automated heart rate occurred at increasing doses of isoproterenol (but not saline) administration. There were again no group differences in heart rate during this period. There was no effect of group $F(1, 28) = .06$, $p = .80$, $\eta_p^2 = .00$, and there were no interactions between condition and group $F(1, 3) = 1.02$, $p = .38$, $\eta_p^2 = .04$, between dose and group $F(1, 4) = .2.12$, $p = .09$, $\eta_p^2 = .09$, or between condition and group and dose $F(1, 12) = 1.19$, $p = .32$, $\eta_p^2 = .05$, suggesting that the mean heart rate increases observed for increasing doses of isoproterenol with the automated measure occurred equivalently (**Figure 30C**).

Systolic blood pressure. A 2 x 4 x 5 repeated measures ANOVA did not find an effect of condition $F(1, 3) = .03$, $p = .99$, $\eta_p^2 = .00$, but did reveal a significant effect of dose $F(1, 4) = 4.35$, $p = .006$, $\eta_p^2 = .17$, $\varepsilon = .820$, on the automated measure of systolic blood pressure. There was no interaction between condition and dose $F(1, 12) = 1.74$, $p < .08$, $\eta_p^2 = .07$, suggesting that changes in systolic blood pressure were not influence by isoproterenol administration. There were no group differences in systolic blood pressure. There was no effect of group $F(1, 28) = .71$, $p = .41$, $\eta_p^2 = .03$, and there were no interactions between condition and group $F(1, 3) = .80$, $p = .50$, $\eta_p^2 = .04$, between dose and group $F(1, 4) = 1.52$, $p = .21$, $\eta_p^2 = .07$, or between condition and group and dose $F(1, 12) = 1.03$, $p = .42$, $\eta_p^2 = .05$. As **Figure 32A** shows, decreases in systolic blood pressure appeared to occur during the first few doses, irrespective of condition. This suggesting that these effects were likely not related to isoproterenol,

Diastolic blood pressure. A 2 x 4 x 5 repeated measures ANOVA revealed a significant effect of condition $F(1, 3) = 25.37$, $p < .0001$, $\eta_p^2 = .54$, and dose $F(1, 4) = 28.58$, $p < .0001$, $\eta_p^2 = .57$, $\varepsilon = .653$, on the automated measure of diastolic blood

pressure. There was also a significant interaction between condition and dose $F(1, 12) = 12.43$, $p < .0001$, $\eta_p^2 = .36$, $\varepsilon = .692$, suggesting that changes in diastolic blood pressure occurred at increasing doses of isoproterenol (but not saline) administration. There were again no group differences in diastolic blood pressure. There was no effect of group $F(1, 28) = .65$, $p = .43$, $\eta_p^2 = .03$, and there were no interactions between condition and group $F(1, 3) = .29$, $p = .82$, $\eta_p^2 = .01$, between dose and group $F(1, 4) = .36$, $p = .76$, $\eta_p^2 = .02$, or between condition and group and dose $F(1, 12) = .45$, $p = .90$, $\eta_p^2 = .02$. As **Figure 32B** shows, decreases in diastolic blood pressure occurred for increasing doses of isoproterenol in an equivalent manner for both groups. Such a decrease in diastolic blood pressure is consisted with the vasodilatory effects of isoproterenol.

7.3.5. Individual heart rates

Given the absence of any group effects, and the striking finding reported by Dimsdale and Mills (2002), an examination of individual heart rate changes during the isoproterenol plus meditation condition was performed. The goal was to identify whether any similar reductions in heart rate could be observed in individual meditators or nonmeditators. The measures that were examined at the individual level included mean heart rate change, mean heart rate, lowest heart rate, and highest heart rate derived from the continuous heart rate waveform during the isoproterenol plus meditation/relaxation and isoproterenol plus rest conditions. Based on the hypothesis that meditation would result in a reduced response to isoproterenol, individual meditators and nonmeditators who displayed the lowest responses were selected for comparison with their respective groups. As **Figure 33A** indicates, there were individuals in each group who displayed a reduced heart rate response and mean heart rate in comparison with their group averages.

Similarly, there were individuals in each group who displayed reduced heart rate maxima and minima when compared with their group averages (**Figure 33B**). However, although these reflect large differences in the magnitude of the response to isoproterenol (compared to each individual's group mean), only one individual (a meditator) appeared to display a significantly reduced heart rate at increasing doses, and only when examined with the 3 second minimum heart rate measure.

7.4 Discussion

As expected, bolus isoproterenol infusions produced dose-dependent increases in heart rate in both groups during a condition of rest. However, contrary to expecations, meditators did not lower their heart rate responses to isoproterenol while practicing meditation. Both meditators and nonmeditators displayed equivalent dose dependent increases in heart rate during conditions of isoproterenol plus rest, and isoproterenol plus meditation/relaxation. This lack of group differences in heart rate was reliable. It was observed for five different measures of heart rate (mean heart rate change, mean heart rate, lowest heart rate during a 3 second period, highest heart rate during a 3 second period, and via automated heart rate monitor), and throughout three epochs that covered the entire time span over which isoproterenol induced changes occur. Equivalent decreases in diastolic blood pressure were also observed in both groups following increasing doses of isoproterenol. These decreases are consistent with the documented vasodilatory effects of isoproterenol on lowering diastolic blood pressure. They are not considered related to the meditation intervention, as they occurred in both isoproterenol conditions.

Since the Dimsdale & Mills study reported a finding in a single individual, an analysis of individual heart rate responses within in each group of participants was undertaken. Of of the measures utilized, there was only one participant who demonstrated an appreciable reduction in heart rate during the meditation plus isoproterenol condition similar to that reported by Dimsdale and Mills (2002) (i.e. a 17 bpm decrease in heart rate from the lowest to the highest dose). Although this finding occurred in a meditator, it was only observed with one measure, the lowest heart rate, which is also the least reliable index of the response to isoproterenol. This finding was no longer present when more robust measures of the heart rate response to isoproterenol (such as the average heart rate and average heart rate change) were examined. Thus it seems highly unlikely that the effect reported by Dimsdale and Mills (2002), although intriguing, applies to the practice of meditation in general.

Several potential factors may explain this discrepancy in findings. The first can be found from the variation in heart rate responses observed at the individual level in the current study. Since the largest reduction in heart rate was observed with a momentary measure (the lowest heart rate during a 3 second period), and since Dimsdale and Mills (2002) did not utilize a continuous measure of heart rate, it is possible that the automatic monitor they utilized recorded the heart rate at the same time the minimum heart rate values occurred during the two doses for which the effect was observed. A second and related reason could be due to measurement error. Although they report that heart rate was measured 60 seconds after the infusion was delivered, it is possible that there was enough variability in measurement to result in completely missing the epoch of interest. I have found large variability in the range of temporal measurement of heart rate using

automated blood pressure monitoring devices in support of this possibility (58 to 93 seconds after initiating measurement). However, despite these potential methodological and procedural limitations, it must be noted that the meditator in Dimsdale and Mills' study demonstrated a heart rate increase at the 1.0 mcg dose, followed by two successive decreases below her resting heart rate. Assuming this was not a spurious finding, such a profound decrease in heart rate could occur during an episode of increased vagal output (as suggested by the authors). Neurocardiogenic syncope is one example of such an increase in vagal output. These episodes are usually preceded by an increase in sympathetic tone (as was observed in the meditator at the 1.0 mcg dose) and can even be triggered by isoproterenol (Kikushima et al., 1999). These episodes are often foreshadowed by symptoms such as lightheadedness, nausea, warmth, pallor and/or sweating, and although the meditator denied experiencing a subset of these (nausea, dizziness or fainting), it is possible that she was not aware of these symptoms given the aforementioned fact that she was in a meditative state that was so deep as to require rousing with an alarm clock. However, since Dimsdale and Mills (2002) only reported the measure of heart rate, it is impossible to determine whether such a reflex occurred. Evaluating this particular meditator's (or others the future) cardiovascular reponse to upright tilt table testing (perhaps even incorporating isoproterenol) would have been useful in excluding this as a possibility.

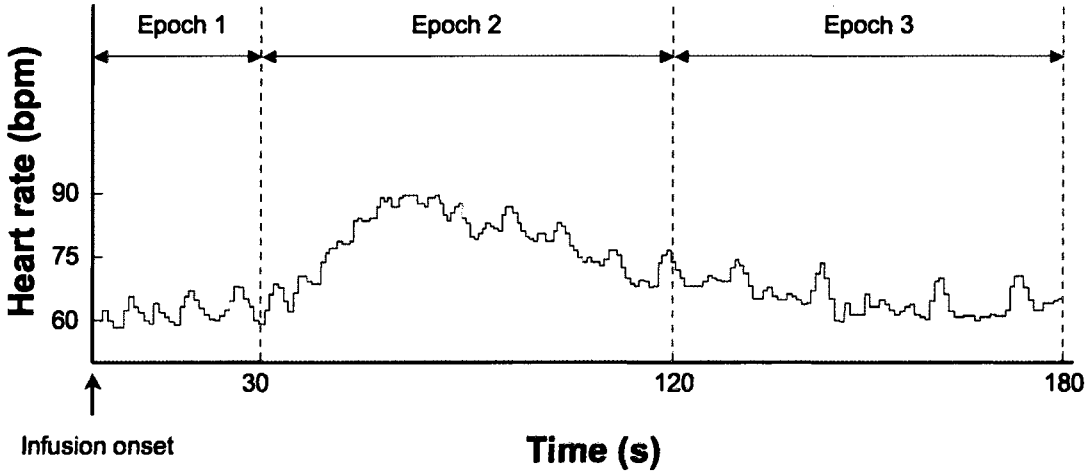
There are several limitations associated with the present study. First, the meditation practice was investigated under highly artificial circumstances. Meditators were meditating in a novel environment, had an intravenous line placed, were attached to various recording equipment and were seated next to two individuals who were observing

them throughout the study. Despite efforts to facilitate the practice (such as a curtain between the investigators and participant, and a dimly lit, quiet room), it cannot be claimed that the meditation and relaxation conditions took place in the usual environment. Second, the current study does not take into account the potential influence of "testing anxiety", that is, concern on the part of the meditators about "performing well". Although meditators did not voice any such concerns, and did not differ from the nonmeditators in questionnaire measures of anxiety this possibility cannot be ruled out. A third limitation is the fact that the meditation plus saline conditions did not appear to lower the heart rate substantially. This could again be due to the artificiality of the environment (thus preventing meditators from authentically engaging in their practice and displaying increased parasympathetic indices). However, ratings of the meditation practice indicated that meditators found their meditation practice during the infusions to be similar to their daily practice, reducing this as a possibility. The lack of heart rate reductions during saline could also be related to the type of meditation participants practiced. For example, some meditations are suggested to increase cardiovascular states whereas others are suggested to decrease them. Since the meditators were not instructed to use their meditation practice to reduce their heart rate (this would have been seen by the practitioners as constraining and interfering with the meditation practice), it is possible that the mediators were performing the former type of meditation. However, reports from the meditators about the nature and quality of their practice did not indicate this as a possibility. Although these limitations warrant consideration, many of them would be similarly imposed by any other scientific study of this meditation and thus cannot be easily obviated. If further investigations of the current topic were continued,

one helpful strategy would be to screen large samples of meditators to identify those individuals who can reliably demonstrate enhanced autonomic regulatory capabilities, and then perform detailed investigation into the cognitive and neurophysiological mechanisms underlying such skills.

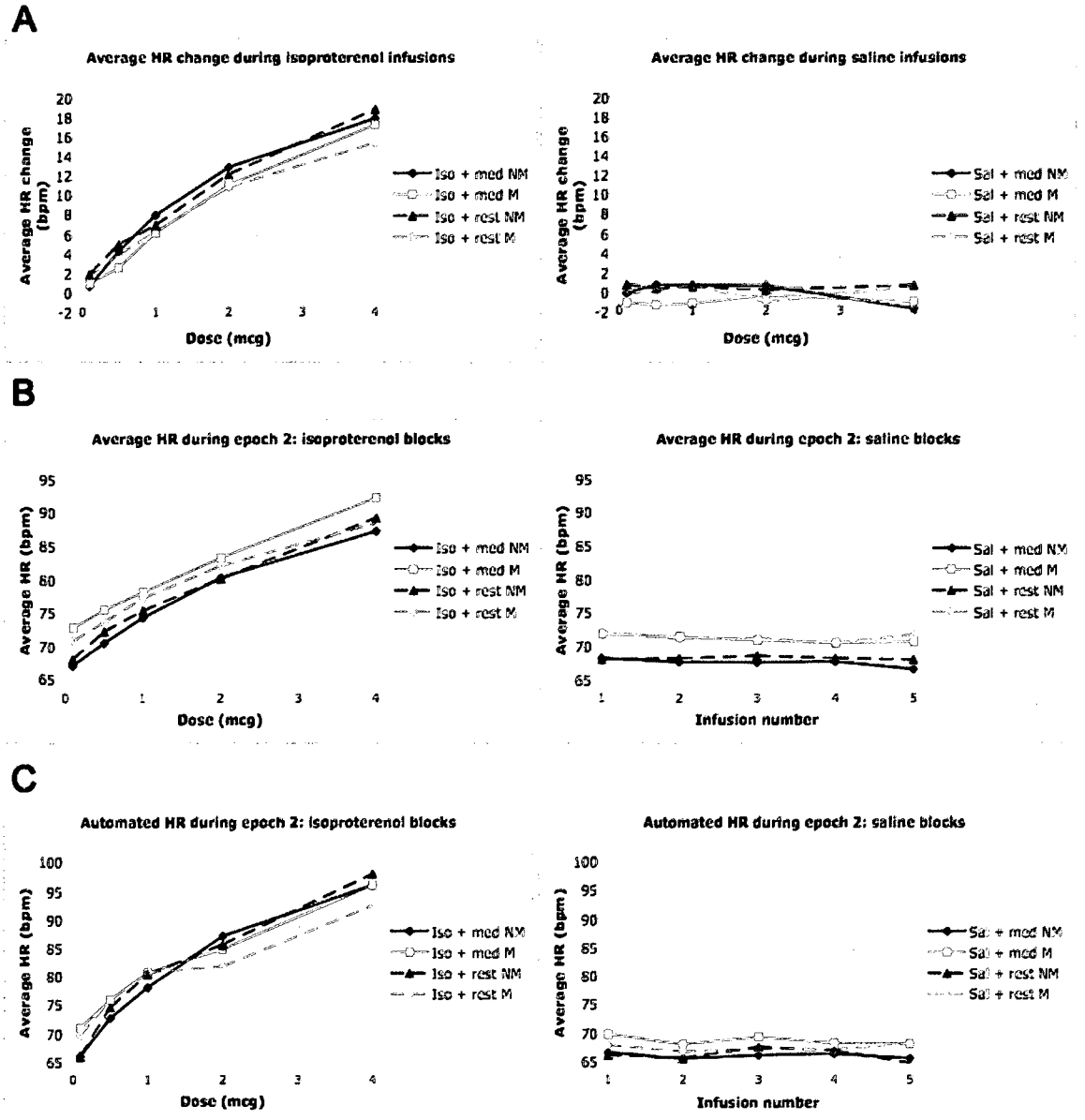
Overall, these results suggest that the formal practice of meditation is not sufficient to counteract the levels of adrenergic physiological arousal that often occur throughout daily life.

Figure 29. Epochs used to derive different measures of heart rate.



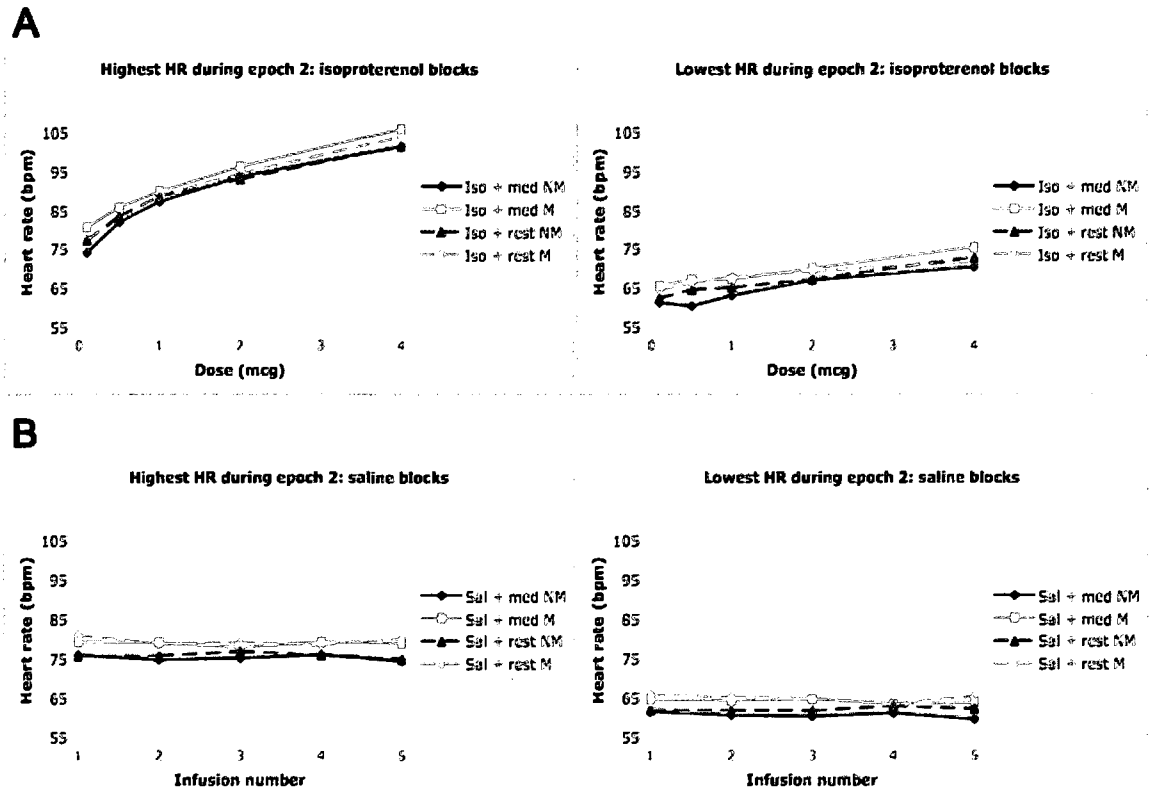
This example shows a typical heart rate response to a 2.0 mcg dose of isoproterenol.

Figure 30. Mean heart rates for both groups during mediation/relaxation and rest.



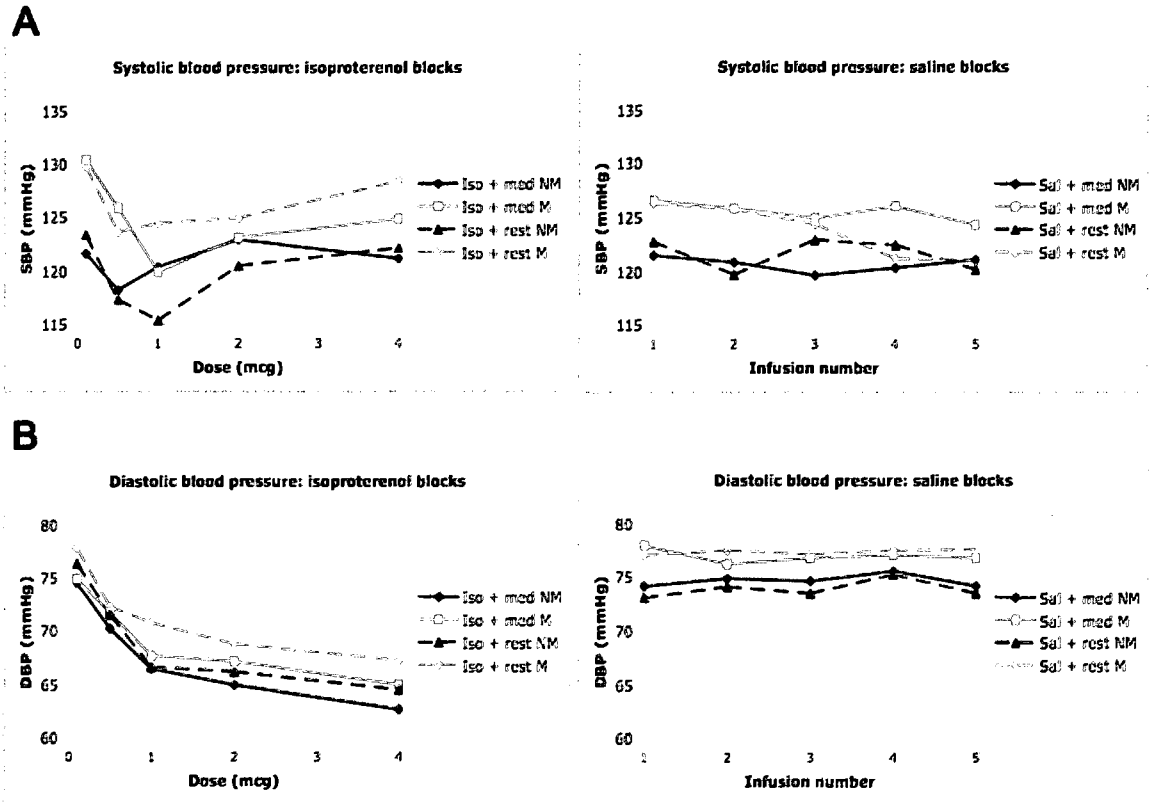
(A) Mean heart rate change (epoch 2 minus epoch 1). (B) Mean heart rate during epoch 2. (C) Mean heart rates measured via automated blood pressure monitor. For purposes of clarity, mean values are displayed without error bars, and the relaxation condition for the nonmeditators is labeled as meditation.

Figure 31. Highest and lowest heart rates for both groups during epoch 2.



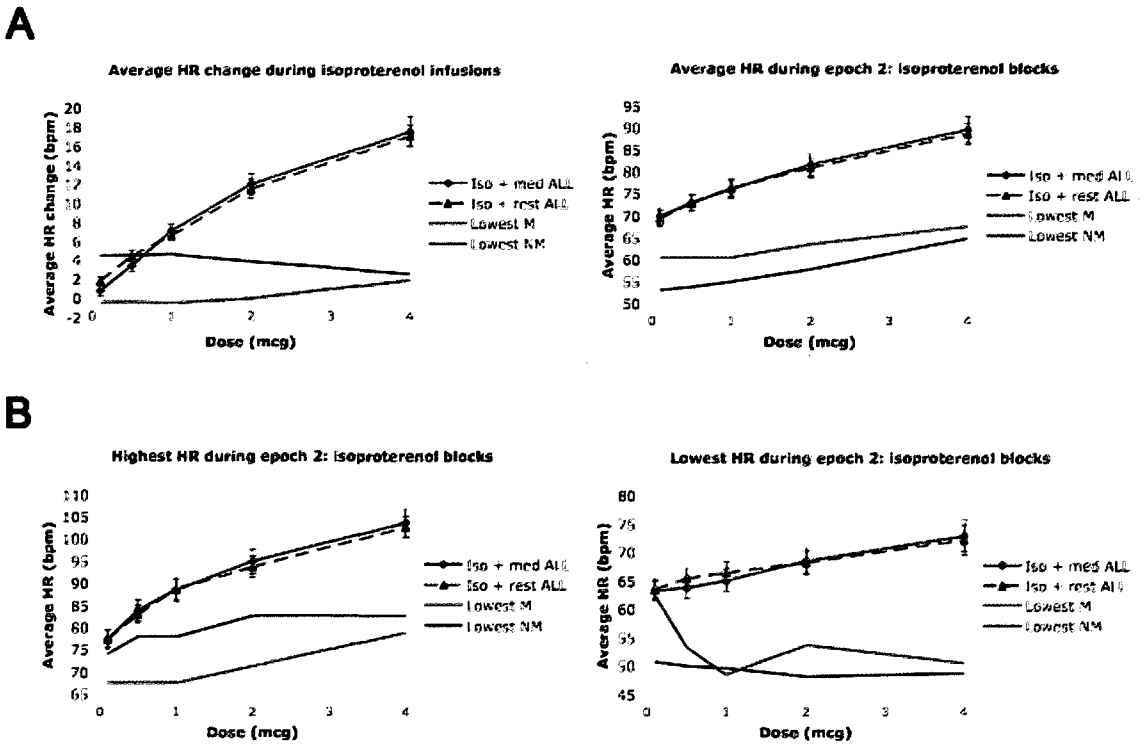
(A) Highest heart rates observed during a 3 second period, averaged across each group. (B) Lowest heart rates observed during a 3 second period, averaged across each group. For purposes of clarity, mean values are displayed without error bars, and the relaxation condition for the nonmeditators is labeled as meditation.

Figure 32. Blood pressure for both groups during meditation/relaxation and rest.



(A) Systolic blood pressure measured via automated blood pressure monitor. (B) Diastolic blood pressure measured via automated blood pressure monitor. For purposes of clarity, mean values are displayed without error bars, and the relaxation condition for the nonmeditators is labeled as meditation.

Figure 33. Global and individual outlier heart rate changes during isoproterenol conditions.



(A) Global mean heart rate change (epoch 2 minus epoch 1) and global mean heart rate observed during epoch 2 for all participants. (B) Global maximum heart rate change and global minimum heart rate change observed during epoch 2 for all participants. The green lines indicate the meditator who displayed the lowest response during the isoproterenol plus meditation condition. The blue lines indicate the nonmeditators who displayed the lowest response during the isoproterenol plus relaxation condition. For purposes of clarity, mean values are displayed without error bars, and the relaxation condition for the nonmeditators is labeled as meditation.

CHAPTER 8. CONCLUSION

The experiments presented in this thesis provide systematic and clear answers to the questions of whether the practice of meditation is associated with increased awareness of heartbeat and breathing sensations, as well as an increased ability to regulate elevations in cardiovascular arousal. The first experiment revealed that extensive meditation experience was not associated with any significant differences in the ability to perceive heartbeat sensations at rest, despite the fact that meditators perceived their performance to be superior than nonmeditators. The second experiment yielded a novel task for reliably inducing and measuring changes in awareness of a range of heartbeat and breathing sensations in all participants. Using this improved design, the third experiment revealed that the shorter term practice of meditation was not associated with increased awareness of heartbeat or breathing sensations, although there was a tendency for the meditators to report changes in cardiorespiratory sensations sooner than nonmeditators. Thus the third experiment yielded the same result as the first experiment, even though appropriate dose dependent changes in awareness were observed in all participants. The fact that identical results were obtained with two divergent methods, in three different groups of meditators, speaks to the reliability and strength of these findings. The fourth and final experiment revealed that engaging in the meditation practice was incapable of reducing pharmacologically induced elevations in physiological arousal, despite some preliminary evidence to the contrary.

Although the current findings were derived using rigorous and unbiased methods, several limitations must be considered. The first limitation relates to the small sample sizes in each experiment, which leads to the possibility that the current studies were not

sufficiently powered to detect the hypothesized effects. Although this is a reasonable concern, power analyses conducted in both of the interoceptive awareness experiments suggested that increasing the sample sizes by an order of magnitude would either result in a very small effect (for heartbeat detection) or no effect at all (for the isoproterenol study). An analysis of the confidence intervals for the isoproterenol study suggested that it was highly unlikely that the critical comparison (namely, the mean difference in maximum cross correlation for the highest doses) would yield an effect if repeated with the present sample size or even with a tenfold increased sample size. For the cardiovascular regulation experiment, there was no evidence that even a single meditator (or nonmeditator) was capable of reducing their heart rate in the face of isoproterenol administration. Whether considering this information individually or together, it seems highly unlikely that the current findings are spurious. The second limitation relates to the use of a cross sectional design. Since the use of such a design limits the ability to make causal inferences, the current studies have only been able to investigate associations between the practice of meditation and the states and traits under investigation. Even if the pattern of findings were in line with my hypotheses, with the present design it would not be possible to conclude that the increased interoceptive awareness or regulation was the direct consequence of meditation experience. For example, I would still not be able to rule out possibility that individuals with greater interoceptive ability gravitate to the meditation practice, perhaps because of the emphasis placed on interoceptive sensations in meditation traditions. A third and related limitation that the present findings are not able to rule out pertains to the possibility that the long term practice of meditation does in fact increase interoceptive awareness. For example, although speculative, it is possible

that the meditators in the present studies started out as poor interoceptors, and as a result of their continued meditation practice were able to reach a normal level of interoceptive ability. A fourth and final limitation relates to the fact that there is likely to have been variation in the types of meditation training received by the meditators in the current sets of studies, even for individuals within the same meditation tradition. For example, many of the Kundalini and Vipassana practitioners received training from different meditation teachers. Although this was not expected to have a great influence on the study, it is possible that differences in instruction (or consequently, differences in daily meditation practice) occurred, and that such differences were capable of obscuring the hypothesized effects.

In the future, one way of overcoming the aforementioned limitations would be to conduct longitudinal investigations into the effects of meditation on interoceptive awareness. Such studies should incorporate randomized recruitment in order to remove the potential bias of expectation of effects. This is not an inconsequential issue, for as the heartbeat detection study showed, the practice of meditation is associated with differences in belief about interoceptive task performance and interoceptive task difficulty. Furthermore, the need for randomized longitudinal designs has been previously emphasized (Ospina et al., 2007). In the interest of practicality, such designs might focus on the effects of shorter periods of intensive training, as often occurs in the context of meditation retreats. These retreats provide a unique opportunity to identify causal effects that might occur over discrete time periods, as a result of standardized training. Indeed, studies incorporating aspects of this design are being increasingly conducted, and are demonstrating promising results (Slagter et al., 2007; Tang et al., 2007).

This work represents the first systematic and detailed investigation of an often presumed facilitating influence of meditation on awareness and regulation of internal body states. Although the findings are predominantly negative, they do address significant gaps in our knowledge of the extent of the basic sensory and autonomic effects of meditation, by providing evidence against some basic assumptions about the practice of meditation. In doing so, these studies have helped to narrow the focus of questions about the types of mechanisms that may be expected to underlie the meditation practice. For example, although it does not appear that meditation broadly increases awareness of heartbeat and breathing sensations, it seems plausible that meditation could slightly facilitate the time course over which such awareness of such sensations develop. This idea is consistent with a series of recent studies that reported improvements in different aspects of attention as a result of meditation training. These increases occurred in the domains of attentional resource allocation (via the attentional blink paradigm) (Slagter et al., 2007), orienting and alerting (Jha et al., 2007) and conflict monitoring (Tang et al., 2007), all of which were obtained using exteroceptive (visual) measures of attention. The isoproterenol study revealed that there was a tendency for meditators to report changes in cardiorespiratory sensations (i.e., the onset and peak) sooner than the nonmeditators. Although it is unclear whether the observed differences truly reflect differences in "interoceptive attention", future studies may investigate this possibility. If meditation does in fact enhance interoceptive attention, it will be important to determine whether this attention is mediated by the same attentional networks implicated by the studies that used exteroceptive measures. Finally, it should be noted that the measures of interoceptive awareness used in the current investigations (e.g., cardiac and respiratory

sensations) reflect only a subset of all of the interoceptive signals available to the brain, and as such, the current conclusions may not necessarily extend to other types of interoceptive sensations.

The present findings invite some intriguing and pressing questions about the effects of meditation. For example, if meditation does not enhance awareness of cardiorespiratory sensations, what, then, is the purpose of practicing awareness of these sensations? Are the present negative findings limited to the domains of cardiac and respiratory sensation (a subtype of interoceptive information)? Does meditation in fact cultivate sensory awareness for other types of interoceptive (e.g., proprioceptive, thermal, gastrointestinal, visceral nociceptive) or somatic (e.g., skin mediated) processes? Does meditation exert an effect at the level of interoceptive attention? Does increased attentional capacity for interoceptive and exteroceptive stimuli engender increased cognitive and emotional awareness, and if so, why? Would increased awareness at these higher levels of cognitive functioning translate to increased emotional resilience and emotional regulatory capabilities? If meditation does not confer an increased capacity to regulate physiological arousal of the body, are there other types of physiological regulatory capabilities that are enhanced? The present work has facilitated the investigation of these issues by clarifying the level of involvement of meditation in lower level bodily processes, and may be considered especially useful given the increasing application of meditation as a complement in alternative medicine.

Beyond meditation, the isoproterenol interoceptive awareness protocol developed here provides a powerful new tool for evaluating the prominent roles that interoceptive sensations have been proposed to play in the experience of emotional states. The

versatility of this approach in inducing brief, rapid and reversible changes in arousal suggests that it may also help in providing new understandings of how conscious and subconscious feedback from the body influences the experience of emotion, how these experiences are mediated within the peripheral and central nervous system, and how they might guide decision making, cognition and behavior.

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