Mindfulness meditation, well-being, and heart rate variability: A preliminary investigation into the impact of intensive Vipassana meditation

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ABSTRACT

Mindfulness meditation has beneficial effects on brain and body, yet the impact of Vipassana, a type of mindfulness meditation, on heart rate variability (HRV) – a psychophysiological marker of mental and physical health – is unknown. We hypothesised increases in measures of well-being and HRV, and decreases in ill-being after training in Vipassana compared to before (time effects), during the meditation task compared to resting baseline (task effects), and a time by task interaction with more pronounced differences between tasks after Vipassana training. HRV (5-minute resting baseline vs. 5-minute meditation) was collected from 36 participants before and after they completed a 10-day intensive Vipassana retreat. Changes in three frequency-domain measures of HRV were analysed using 2 (Time; pre- vs. post-Vipassana) × 2 (Task; resting baseline vs. meditation) within subjects ANOVA. These measures were: normalised high-frequency power (HF n.u.), a widely used biomarker of parasympathetic activity; log-transformed high frequency power (ln HF), a measure of RSA and required to interpret normalised HF; and Traube–Hering–Mayer waves (THM), a component of the low frequency spectrum linked to baroreflex outflow. As expected, participants showed significantly increased well-being, and decreased ill-being. ln HF increased overall during meditation compared to resting baseline, while there was a time ∗ task interaction for THM. Further testing revealed that pre-Vipassana only ln HF increased during meditation (vs. resting baseline), consistent with a change in respiration. Post-Vipassana, the meditation task increased HF n.u. and decreased THM compared to resting baseline, suggesting post-Vipassana task-related changes are characterised by a decrease in absolute LF power, not parasympathetic-mediated increases in HF power. Such baroreflex changes are classically associated with attentional load, and our results are interpreted in light of the concept of 'flow' — a state of positive and full immersion in an activity. These results are also consistent with changes in normalised HRV reported in other meditation studies.

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1. Introduction

In the last two decades, psychological interventions derived from mindfulness meditation practices have been increasingly used to treat a variety of stress, pain and anxiety-related conditions (Hofmann et al., 2010). Mindfulness refers to the state of being attentive to and aware of what is taking place in the present (Brown and Ryan, 2003; Shapiro, 2009); mindfulness meditation comprises a variety of techniques that help focus attention in a non-analytical way and avoid discursive, persistent, or obsessive thoughts (Shapiro, 1980). These techniques – such as quieting the mind, and exercising self-control – can have a profound influence on mind and body, and show promise as an alternative tool to regulate emotions, mood, and stress. However, the acute and longer-term concomitants of mindfulness meditation training, and potential mechanisms of action are still not well understood. In particular, there is a need to further understand the effects of meditation on the autonomic nervous system, a major component of emotional experience. While limited research has examined the effects of Zen meditation, different styles may have distinctive effects. For instance, Zen meditators show distinctive respiration changes (Lehrer et al., 1999) that are not evident in other styles such as yoga (Sarang and Telles, 2006) or traditional

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Chinese practices (Tang et al., 2009). Here we examine the impact of a particularly intensive form of mindfulness meditation – Vipassana – on heart rate variability, an important psychophysiological marker of mental health and wellbeing.

1.1. Meditation and well-being

One of the goals of mindfulness is to allow thoughts to arise, be examined dispassionately, and allowed to fade, without practitioners being emotionally influenced by their contents. This process is a fundamental part of Vipassana meditation (Gethin, 1998). This technique is also similar to the reappraisal strategy for emotion regulation, which can serve to decrease subjective, physiological and neural responses, rather than increasing them as is the case with emotion suppression (Gross and Levenson, 1997; Gross, 1998; Goldin et al., 2008).

Mindfulness techniques appear to be linked in a variety of ways to well-being. Important behavioural examples include reduction in distractive and ruminative thinking (Jain et al., 2007) and symptoms of anxiety and mood disorders (Goldin and Gross, 2010; Hofmann et al., 2010), and improved emotion regulation (Arch and Craske, 2006). Individual differences in the ability to regulate emotional responses are also related to differences in mindfulness, even in non-meditators (Modinos et al., 2010). These findings suggest the possibility that mindfulness meditation influences well-being via changes in emotion regulation. Furthermore, trait mindfulness was associated with wider prefrontal and diminished amygdale activity during an affect labelling task in non-meditators, suggesting a possible mechanism for the role of mindfulness in emotion regulation (Creswell et al., 2007).

Neural and physiological benefits found to be associated with meditation include: increases in immune system activity and left-sided anterior activation, a pattern associated with positive affect (Davidson et al., 2003); decreased amygdale response to emotional stimuli (Desbordes et al., 2012) and increased brain connectivity (Luders et al., 2011). Moreover, long-term meditators had greater grey matter density in regions previously found to be involved in meditation including right anterior insula (involved in interoceptive awareness), left inferior temporal gyrus and right hippocampus and right orbito-frontal cortex (Hölzel et al., 2008; Luders et al., 2009). These particular studies are relevant because of the overlap with regions of the central autonomic network related to heart rate variability, especially insular and orbitofrontal cortices (Thayer and Lane, 2000; Thayer et al., 2009). Experienced meditators demonstrated increased cortical thickness in insula and prefrontal cortices compared to matched controls (Lazar et al., 2005), as well as larger gyrification in regions including left precentral and right fusiform gyrii, and the insula (Luders et al., 2012). These findings, taken together, suggest that meditation has dramatic long-term structural effects on the brain.

Vipassana is a widespread technique of mindfulness meditation, derived from Buddhist practice, based on objective observation of physical sensations in the body. Awareness of the breath is also used as an aid to concentration. It is taught in a standardised manner throughout the world, and involves up to 100 h of intense meditative practice over a 10-day period. This intense standardised training is ideally suited to examining the effects of mindfulness meditation on well-being and related physiological changes.

1.2. Well-being and heart rate variability

Heart rate variability (HRV) is a measure of beat-to-beat variability in heart rate that is mediated by the autonomic nervous systems. Parasympathetic influence on HRV is primarily mediated by the vagus nerve, which can provoke rapid changes from cardiac cycle to cardiac cycle, and is primarily responsible for fluctuations in respiratory sinus arrhythmia (RSA) and high frequency HRV (HF) (Dexter et al., 1992; Berntson et al., 1993). Sympathetic influence is primarily controlled by release of norepinephrine and catecholamines, precluding direct

manifestation in short term fluctuations (Berntson et al., 1993) Sympathetic neural activity can alter cardiac behaviour only slightly from beat to beat (Levy et al., 1993), and thus RSA measured through HF HRV is often used as a biomarker of pure PNS activity. That is, the level of vagal outflow will be reflected in the magnitude of RSA, which is typically measured at the speed of normal breathing, at cycles from approximately 3 to 7 s (i.e. 0.15–0.4 Hz). THM, on the other hand is component of low frequency (LF) HRV which reflects an oscillation of arterial pressure (Julien, 2006). Recent studies suggest that low frequency power more closely approximates baroreflex outflow, rather than sympathetic activation (Moak et al., 2009; Goldstein et al., 2011).

Amongst other things, HRV reflects the capacity of the central autonomic network (CAN) – including the prefrontal cortex, central nucleus of the amygdala, hypothalamus and brainstem – to meet and adapt to environmental demands (Thayer and Friedman, 2002). HRV underpins an individual's capacity to regulate their emotions (Geisler et al., 2010), and may be key to psychological flexibility (Kashdan and Rottenberg, 2010).

HRV is reduced in patients with cardiovascular disease (Nolan et al., 1996), and reduced HRV is an indicator of risk of cardiac and all-cause mortality (Dekker et al., 2000; Tsuji et al., 1996). A number of studies and reviews (e.g. Kemp et al., 2010; Kemp et al., 2012) have indicated that HRV is reduced in patients with depression and anxiety, even without cardiovascular disease. While studies have often focused on links between decreased HRV, negative emotions and poor physical health, increased HRV is related to well-being (Kemp and Quintana, 2013–in this issue) over and above reductions in negative affect (Boehm and Kubzansky, 2012). There is growing evidence that positive psychological attributes such as mindfulness are independently related to cardiac health and autonomic function (DuBois et al., 2012), including individual differences in resting respiratory sinus arrhythmia (RSA) (Oveis et al., 2009) and THM (Fuller, 1992).

1.3. Meditation and HRV

The effects of Vipassana on HRV have not to our knowledge been systematically researched, although several other mindfulness based meditation techniques have been examined in more detail in novice and experienced meditators.

The acute task-related cardiovascular effects of Zen meditation compared to resting baseline in practitioners with varying levels of experience have been better studied than Vipassana. Lehrer et al. (1999) found that respiration rates fell dramatically during Zen breathing meditation in experienced meditation practitioners. High frequency (HF) HRV decreased as a percentage of total variance (although there were no significant changes for absolute HF power). Total heart rate (HR) oscillation amplitude increased, as did absolute low frequency (LF) power — reflecting a shift in RSA towards lower-frequency waves. These findings confirmed that Zen breathing meditation results in an increase in low and very low frequency HR oscillations, shifting the majority of HRV spectral power into the low frequency band. Within-subjects shifts in RSA during Zen meditation compared to resting baseline varied with experience (Peressutti et al., 2010). Strong HF oscillations were observed in novices; while for the most experienced practitioners, variance centred in the LF range and was linked to RSA, being associated with decreased breathing rate during meditation (Peressutti et al., 2012).

Much of this research focused on meditation tasks involves slow breathing, relative to a normal breathing condition during a resting baseline. Very different task effects were found for an inward-directed attention meditation task which did not involve controlled respiration. During this task experienced Zen meditators exhibited increases in normalised HF (HF n.u.) and corresponding decreases in normalised LF and LF/HF ratio, compared to resting non-meditators and to their own resting baseline (Wu and Lo, 2008). A number of studies have reported similar acute HF increases after other styles of meditation,

e.g. yoga-based cyclic meditation, (Sarang and Telles, 2006; An et al., 2010).

Differences between studies in which meditation acutely increased HF and those in which LF increased, can be partially explained by the influence of respiration rate on HRV (Schipke et al., 1999), especially as respiration was particularly slow in the study by Lehrer et al. (1999). The acute effects of being in a state of meditation, however, cannot be entirely reduced to breathing differences; mindfulness meditation appears to have an effect over and above simple breathing interventions. A similar pattern to that found by Wu and Lo (2008) – increased normalised HF power in meditation – emerged when novices were trained to perform a mindfulness of breathing task at a breathing pace of .25 Hz, and compared to a resting control in which they performed the same paced breathing. This allowed the acute effects of the meditation task to be separated from changes in respiration rate, and demonstrated that mindfulness meditation even with deliberately paced breathing had effects over and above the effects of paced breathing alone (Murata et al., 2004; Takahashi et al., 2005).

While the above studies focused on acute changes from being in a state of meditation, rather than longer-term changes in resting baseline HRV, there is evidence of changes in resting baseline HRV as a result of mindfulness meditation training. Tang et al. (2009), compared meditation-naïve participants who were given a short course of meditation involving mindful awareness with a relaxation control. Meditation resulted in decreased stress, calmer breathing, and increased normalised HF within subjects (vs. resting baseline measures), and between subjects (vs. the relaxation group).

The majority of these results report normalised high frequency HRV (HF n.u.), which has the distinct advantage of being comparable as a measure of vagal outflow between studies using different methods of spectral analysis (Task Force, 1996). However, HF n.u. suffers from an unavoidable interpretative problem — without comparative measures of raw or adjusted power for individual frequencies, changes in those frequencies may be obscured by their being reported as proportions. For example, if LF power decreases enough, HF n.u. may go up dramatically while spectral power in the HF band decreases. A change in normalised HF could be the result of increased HF power, decreased LF power, or a combination. Normalised units "should always be quoted with absolute values of LF and HF power in order to describe in total the distribution of power in spectral components" (Task Force, 1996, p. 358). Thus a complete description also requires the reporting of absolute units — a recommendation of the Task Force often neglected in HRV research. No other proportional units such as normalised LF power or LF/HF ratio need be reported, as they are equivalent to HF n.u. (Burr, 2007).

1.4. The present study

The primary goals of the current study were to examine the effect of Vipassana meditation on psychological measures related positively and negatively to well-being, and to extend research on the cardiovascular effects of mindfulness meditation to the techniques of Vipassana meditation. The Vipassana retreat studied here is of particular interest because of the intensity of training — maximising the opportunity to observe resting baseline and acute meditation-related associations with HRV. Vipassana meditation does not focus on controlled breathing or chanting, avoiding certain complications of the relationship between HRV and respiration. Finally, the Vipassana retreat is taught in a standardised manner, enabling easier replication of findings. We also sought to examine the effects of Vipassana training on psychological measures of well-being.

Because of the difficulties associated with direct interpretation of normalised HRV frequency measures, this study focused on measures of absolute HF and LF powers, as well as the normalised measures more commonly reported. We included the high frequency bands corresponding with respiratory sinus arrhythmia (RSA; 0.15–0.40 Hz)

and the low frequency Traube–Hering–Mayer wave (THM; 0.06 to 0.10 Hz). Both of these specifically capture the expected bands in which change during a meditation task might be provoked due to an alteration in breathing. The THM wave specifically should be sensitive to the slow breathing effects typically observed in meditation, as the RSA contribution interacts with the baroreflex (Berntson et al., 1997). THM was included as a low frequency measure of baroreflex function, which was considered important in order to clarify possible effects in normalised HF. However no a priori hypotheses were put forward for THM in terms of time, task or interaction effects of meditation.

While the neural correlates of Vipassana meditation have been examined both in terms of state effects (Hölzel et al., 2007) and correlates of long-term practice (Hölzel et al., 2008), to our knowledge, there is no research available on the cardiovascular effects of Vipassana meditation, either acute or longer-term changes in resting baseline HRV. It is as yet unclear whether intensive Vipassana meditation has similar effects on HRV as other mindfulness techniques.

This primary goal of this experiment was to determine the effects of 10 days of intensive Vipassana meditation training on measures of well-being including frequency measures of heart rate variability. It was expected that intensive Vipassana meditation training would result in distinct changes in HF measures of HRV, both at the acute level with changes from resting baseline to the meditation task, and longer-term changes after Vipassana training, compared to before.

(1) It was hypothesised that there would be differences over time, comparing participants after Vipassana Meditation training to their pre-Vipassana resting baseline measures.

a. Well-being was expected to improve after meditation training compared to before. Increases were expected in measures of well-being and decreases were predicted in ill-being.

b. Before meditation training, positive measures of well-being were expected to correlate positively with resting baseline frequency-domain (ln HF, HF n.u., THM) HRV measures. The reverse pattern was expected for ill-being measures.

c. High frequency (ln HF and HF n.u.) HRV measures were expected to increase post- compared to pre-Vipassana, representing main effects of time.

(2) Both before and after Vipassana training, HF HRV measures were expected to increase in the meditation task compared to the resting baseline, representing a main effect of task.

(3) These HRV main effects of time (pre vs. post meditation training) and task (resting baseline vs. meditation task) were further expected to interact. The differences between the meditation task and the resting baseline were expected to be more pronounced after Vipassana training, compared to before.

2. Methods

2.1. Participants

A total of 36 participants (16 males, 20 females; mean age = 43.8 years, 11 participants did not report their age) took part in the study. Participants registered to attend a 10-day intensive meditation course in the tradition of S. N. Goenka (a full description of course schedule available from www.dhamma.org) at the Vipassana Meditation Centre (VMC) in Blackheath, N.S.W, Australia. The VMC then contacted participants who had enrolled in the meditation course for the first time, to inform them about the study and interested participants contacted the researchers via email, to arrange an appointment on the day before the course. The experimental protocol was approved by the University of Sydney Human Research Ethics Committee (Protocol number 10-2011/13980). All participants gave informed consent and all procedures were in accordance with The National Statement on Ethical Conduct in Research Involving Humans(2007) issued by the

National Health and Medical Research Council (NHMRC) in accordance with the NHMRC Act, 1992.

2.2. Procedure

Data were collected at the Vipassana Meditation Centre on the day before the course, and then at the University of Sydney or elsewhere as convenient as soon as possible after the course (allowing for a pre–post meditation training comparison). On average data for the second appointments were collected 4.3 days after the end of the course (SD 4.04).

All data were collected between 3:00 and 6:00 p.m. in order to control for time of day effects on HRV, all data were collected with participants seated in an upright posture, and data were collected from up to 5 participants at a time. Participants were asked to avoid food and drinks, including water, for 2 h before data collection, and to avoid caffeine, alcohol and nicotine for 24 h, in order to avoid known influences of these factors on autonomic state (Fagius and Berne, 1994; Routledge et al., 2002; Sjoberg and Saint, 2011).

Tasks included a 5-minute resting baseline recording in which participants were instructed to simply sit quietly with their eyes open, and a 5-minute eyes closed Anapana (mindfulness of breathing) meditation exercise, in which participants were instructed to breath naturally and to be mindful of each breath as it enters and leaves the body. Task order was counterbalanced, although all participants completing the experiment together were given the same task order for reasons of practicality. All participants performed tasks in the same order at both assessments. During the tasks, participants' heart rate and R–R interval data (the interval between successive heart beats measured from the peak of the R wave) were collected using a Polar watch RS800CX with chest strap. Despite some debate as to the utility of this system (Wallén et al., 2012; Quintana et al., 2012), reliability and validity of the Polar monitors to measure R–R intervals is acceptable (Weippert et al., 2010). Participants also completed a number of questionnaires after HRV data had been collected.

2.3. Questionnaire measures

Several measures were used to examine the effects of Vipassana training over time on well-being and ill-being. Measures considered positively related to well-being included; satisfaction with life (SWL; Diener et al., 1985), mindfulness (MAAS; Brown and Ryan, 2003), and the positive subscale of the Positive and Negative Affect Scale (PANAS; Watson et al, 1988). Measures considered to be related to ill-being were all subscales of the Depression Anxiety Stress Scale (DASS-21; Lovibond and Lovibond, 1995), as well as overall negative affect measured via the negative affect subscale of the PANAS.

2.3.1. Positive measures of well-being

The Satisfaction with Life Scale, (SWL; Diener et al., 1985), uses 5 items (e.g., "In most ways my life is close to ideal") rated from 1 ("Strongly disagree") to 7 ("Strongly agree") with a higher mean score reflecting greater life satisfaction. The scale shows good test–retest reliability (2-month test–retest correlation = .82) and internal consistency ($\alpha = 0.87$) (Diener et al., 1985), as well as showing high convergence with other self and peer-reported measures of satisfaction and well-being in elderly as well as college age samples (Pavot et al., 1991).

The Mindfulness Attention Awareness Scale, (MAAS; Brown and Ryan, 2003) is a single factor scale which uses 15 items (e.g., "I find myself doing things without paying attention") rated from one ("almost always") to six ("almost never"); higher mean scores indicate greater trait mindfulness. Cronbach's α indicated good internal reliability ($\alpha = 0.89$) and no significant gender differences in a college sample, (MacKillop & Anderson, 2007), and in a general sample of non-college adults ($\alpha = 0.87$) (Brown and Ryan, 2003).

The Positive and Negative Affect Scale, (PANAS; Watson et al, 1988), comprises two 10-item mood scales, measuring positive and negative

affect respectively. Participants rate each item on a 5 point scale from 1 ("very slightly or not at all") to 5 ("extremely") to indicate the extent to which they have felt a particular way (e.g., "excited" in the positive affect scale or "ashamed" in the negative scale) over a specified period, in this case over the past week. Internal reliability across student and adult populations ranged from .86 to .90 for the positive affect and .84 to .87 for negative affect. Test–retest correlations have indicated good reliability, and the scale has been validated by comparison to other measures of positive and negative affect, as well as related measures such as depression, anxiety and psychological distress (Watson et al., 1988). The positive affect subscale was considered to be a positive measure of well-being, while the negative scale was considered a measure of ill-being. In the present sample, reliability coefficients (Cronbach's alpha) for all well-being scales pre-meditation was good, ranging from alpha = .848 to alpha = .892.

2.3.2. Measures of ill-being

The Depression, Anxiety and Stress Scales, (DASS-21; Lovibond and Lovibond, 1995) is a 21-item questionnaire that comprises three subscales of 7 items indexing depression (e.g., "I couldn't seem to experience any positive feeling at all"), anxiety (e.g., "I felt scared without any good reason") and stress (e.g., "I found it hard to wind down"). Items are scored from 0 ("Did not apply to me at all") to 3 ("Applied to me very much, or most of the time"). Scores are summed across items within each subscale, with a higher score representing greater severity. Subscales had good reliability (Cronbach's $\alpha = .88$ for Depression, $\alpha = .82$ for Anxiety, $\alpha = .90$ for Stress) and have demonstrated good convergent and discriminant validity (Henry and Crawford, 2005; Crawford and Henry, 2003).

In addition, the negative affect scale of the PANAS (Watson et al., 1988), discussed above, was used as another negative well-being measure. In the present sample, reliability coefficients (Cronbach's alpha) for all ill-being scales pre-meditation was except anxiety was good, ranging from alpha = .795 to alpha = .928. The Anxiety scale was less reliable in the present sample, alpha = .641.

2.4. HRV measures, data reduction and analysis

While any number or HRV measures can be calculated from R–R series, this paper focused on the frequency domain. These measures are of greater interest because of the association of changes in these bands with the modulation of the autonomic nervous system — they better represent the response of certain physiological subsystems (compared to time-domain measures). These frequency measures have also been more studied in previous meditation research.

For the HRV data, artefact removal was performed manually using the software CardioEdit and CardioBatch, according to the method developed by Porges (1985). The data were visually inspected for errors and 35 recording periods with a proportion of errors over 5% were discarded; representing 24.3% of the 144 hrv files across 4 recordings each for 36 participants. Of these, 74% (26 recording periods) were due to hardware failure, and 26% (9 recording periods) were incidental. Participants with errors in any section (16 in total) were excluded from repeated measures analysis. After artefact removal each heart rate series was interpolated to form a time series, detrended via polynomial filter, then bandpassed to extract the frequency of interest (HF: .15hz to .40hz, THM component of LF: .06 to .10 Hz) and natural-log transformed. This method corrects for potential non-stationarity and returns equivalent estimates to frequency analysis. These methods were used for the measures of absolute HF and LF power. Based on the error-corrected data, normalised power in the high-frequency band (HF n.u., 0.15–0.4 Hz) was computed using KUBIOS version 2.1 (Tarvainen and Niskanen, 2008). The resting baseline R–R recordings for the first session were truncated to remove errors for 2 participants. Files were kept if they were not significantly truncated — i.e. truncation removed less than 5% of continuous data. If an error period was removed, the values from the remaining series was used, or if plural

periods were created by truncation, then the RSA and THM values were averaged in proportion to their comparative length.

Statistical analysis was conducted using SPSS Version 16. Effects of meditation on psychological well-being were examined using paired samples tests for each of the self-report measures, comparing scores after the intensive meditation retreat with pre-meditation baselines. Correlations between resting baseline HRV and the self-report measures before the meditation course were examined to provide a validation of the expected relationships between HRV and well-being and a foundation on which the effects of meditation can be interpreted.

The effects of time, task, and the interactions between these factors were examined using a 2 (Time; pre- vs. post-Vipassana) × 2 (Task; resting baseline vs. meditation) within subjects ANOVA for each of the HRV measures separately. Given the complex and sometimes inverse relationships between these measures, an overall MANOVA was not considered meaningful. In order to statistically examine effects in HRV more closely, and to investigate planned comparisons relating to specific hypotheses, paired samples tests were conducted to with respects to the interaction of task with time (i.e. our third hypothesis). There are strong reasons not to divide power amongst multiple HRV measures. While the simple effect analysis was the main point of interest for hypothesis 3, the omnibus ANOVA was investigated in order to examine hypothesis 2 and the last part of hypothesis 1. The interaction component of the omnibus ANOVA was also of interest, in order to characterise any observed main effects. There are strong reasons not to divide power amongst multiple HRV measures. Controlling for multiple comparisons reduces Type 1 error but also increases Type 2. Instead, the decision was taken to focus on reporting effect sizes, following Cohen (1994), and to examine patterns of results. In interpreting effect size we have followed the guidance of Cohen (1988) for correlations (small, $r = 0.1$; medium, $r = 0.3$; large, $r = 0.5$), t-tests (Cohen's d and dz: small, $d = 0.2$; medium, $d = 0.5$; large, $d = 0.8$) and ANOVA (Cohen's f: small, $f = 0.1$; medium, $f = 0.25$; large, $f = 0.4$)

3. Results

3.1. Impact of 10 days of meditation on psychological well-being

Participants improved significantly on all positive psychometric measures of psychological health and well-being, including positive affect, satisfaction with life, and mindfulness (see Table 1). There were also significant decreases in depression, stress and negative affect, measures related to ill-being (Table 1). All changes represented medium or large effect sizes. The only exception was the Anxiety subscale of the DASS, which did not change.

This lack of result for anxiety is not surprising; two questions in this subscale relate to awareness of bodily sensations, which was expected to be increased by the meditation course independently of

anxiety ("I was aware of dryness in my mouth" and "I was aware of the action of my heart in the absence of physical exertion"). Interestingly, when these items were removed, improvement in DASS anxiety results came closer to resembling those for the other subscales, albeit at trend levels.

3.2. The relationship between resting baseline HRV and well-being

Absolute HF power was negatively related to negative affect (PANAS_Negative) ($r_{20} = -.493$, $p = .020$), but not to other measures, while HF n.u. did not correlate with any of the well-or ill-being measures. THM was positively related to positive affect (PANAS_Positive) ($r_{20} = .423$, $p = .050$), and correlated negatively with depression ($r_{21} = -.482$, $p = .020$) and stress ($r_{21} = -.496$, $p = .016$). All of these represented medium effect sizes.

3.3. The effects of 10 days of meditation on HRV

There were no significant main effects of time (pre- vs. post-Vipassana) on HRV (Fig. 1). Effects on HRV frequency measures were not significant for absolute HF power ($F_{1,19} = 1.293$, $p = .27$, Cohen's $f = .261$), normalised HF power ($F_{1,19} = 1.596$, $p = .222$, Cohen's $f = .291$), or THM, ($F_{1,19} = 2.217$, $p = .153$, Cohen's $f = .341$).

3.4. Overall effects of the meditation task on HRV measures; compared to a resting baseline

For absolute HF power (ln HF) the main effect of task was significant, with greater average HF during the meditation task compared to the resting baseline ($F_{1,19} = 9.564$, $p = .006$, Cohen's $f = .710$), representing a large effect size (Fig. 1a). The effect on HF n.u. was in the same direction, but it failed to reach significance despite representing a large effect size, ($F_{1,19} = 3.223$, $p = .089$, Cohen's $f = .412$) (Fig. 1b). For THM, the main effect of task did not approach significance ($F_{1,19} = 0.877$, $p = .361$, Cohen's $f = .215$) (Fig. 1c).

3.5. Changes in meditation task effects after Vipassana training: interactions of time and task

A significant time by task interaction was observed for THM, ($F_{1,19} = 4.922$, $p = .039$, Cohen's $f = .509$), a finding associated with a large effect size. Before the Vipassana course, there was no significant difference between the meditation task and resting baseline ($t_{19} = -.520$, $p = .609$, Cohen's $dz = .12$). After the Vipassana course, however, THM was decreased in the meditation task compared to resting baseline, representing a medium effect size ($MD = .40$, $SD = .55$) ($t19 = 3.275$, $p = .004$, Cohen's $dz = .73$).

Table 1
Changes in positive and negative self report measures of well-being and ill-being after Vipassana meditation training.

Measure	Pre-Vipassana		Post-Vipassana		d.f.	t	Sig.	Effect size
	Mean	SD	Mean	SD				
Positive measures: well-being								
Positive Affect (PANAS)	36.226	7.967	40.080	6.934	31	−2.873	0.007	0.508
Satisfaction with Life (SWL)	24.848	6.221	28.212	6.229	32	−4.517	0.000	0.786
Mindfulness (MAAS)	4.219	0.651	4.863	0.717	31	−5.223	0.000	0.923
Negative measures: ill-being								
Depression (DASS)	6.630	8.617	2.970	6.085	32	3.183	0.003	0.554
Anxiety (DASS)	6.242	6.016	5.455	4.221	32	0.794	0.433	0.138
Modified Anxiety[a] (DASS)	4.291	5.621	2.618	3.859	32	1.921	0.064	0.334
Stress (DASS)	12.970	7.334	4.364	4.885	32	6.285	0.000	1.094
Negative Affect (PANAS)	19.825	6.668	13.313	3.632	31	5.474	0.000	0.968

Notes: Effect size is measured using Cohen's dz. PANAS = Positive and Negative Affect Schedule, SWL = Satisfaction with Life Scale, MAAS = Mindful Attention Awareness Scale. DASS = Depression, Anxiety and Stress Scale-21 item version,

[a] Modified Anxiety was calculated by removing the 2 items of the scale which overlapped particularly with mindful awareness of bodily sensations, i.e. Q2 and Q 19.
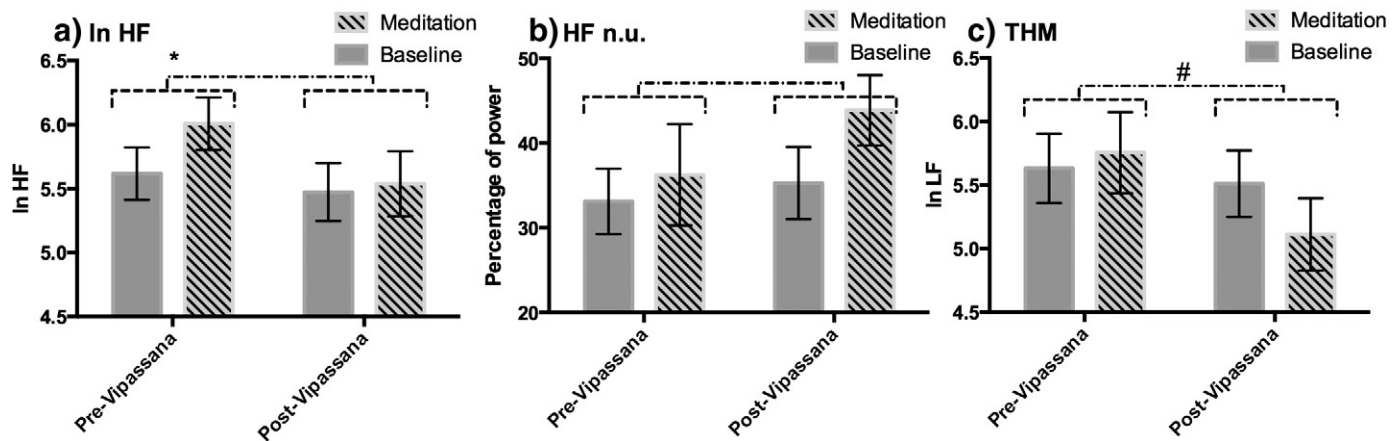
Fig. 1. Means (SEM) by time and task for frequency domain HRV measures; (a) log transformed absolute HF power, (b) normalised HF power, and (c) log transformed THM power. Note: Significant main effects ($p < .05$) are marked with *, significant interactions are marked with #.

For ln HF the time × task interaction only approached significance, although the finding was associated with a large effect size ($F_{1,19} = 3.20$, $p = .090$, Cohen's $f = .410$) (Fig. 1a). Planned t-tests revealed a significant increase in ln HF in the meditation task compared to resting baseline; again, a finding associated with a large effect size, ($MD = .39$, $SD = .46$) ($t_{19} = -3.753$, $p = .001$, Cohen's $dz = .84$), but only before Vipassana training. After the Vipassana course, the meditation task did not impact on ln HF relative to resting baseline ($t_{19} = -.507$, $p = .618$, Cohen's $dz = .11$).

For HF n.u., the time by task interaction did not approach significance ($F_{1,19} = .620$, $p = .441$, Cohen's $f = .182$) (Fig. 1b). However, in light of the above effects for absolute frequency-domain measures, we continued as planned to further examine the effects of task at each time-point. Unlike the pattern for ln HF, no difference between the resting baseline and the meditation task before the meditation course ($t_{19} = -.539$, $p = .596$, Cohen's $dz = .12$) was observed. By contrast, after the meditation course, HF n.u. was increased in the meditation task compared to baseline ($MD = 8.60$, $SD = 14.97$) ($t_{19} = -2.568$, $p = .019$, Cohen's $dz = .57$), representing a medium effect size. These findings were opposite to those observed for THM (Fig. 1c).

4. Discussion

The proposed links between HRV, well-being, and ill-being were a starting point for this research. As expected, there were substantial and consistent improvements in well-being and reductions in measures of ill-being after Vipassana training. The only exception was anxiety as noted above. Overall, all four significant correlations between HRV and questionnaire measures were in the expected directions although many of the expected correlations were not significant. Increases in normalised HF in the meditation task post-Vipassana were in line with previous studies of meditation, while changes in the absolute frequency measures (ln HF and THM) were partially as expected. The pattern of task results has interesting implications for interpreting the effects of meditation in the light of 'flow,' a state of positive immersion in an activity (Csíkszentmihályi, 1996).

4.1. Meditation and well-being

Changes in self-report measures of well-being confirmed the first hypothesis. After 10 days of intensive Vipassana meditation, participants improved in well-being; with increases in all measures of well-being, and decreases in all ill-being measures but anxiety, which included measures of awareness of bodily states. These results are particularly interesting given the relationships between ill-being and decreased HRV, well-being and increased HRV, and findings suggesting that psychological well-being can have cardioprotective effects (Boehm and Kubzansky,

2012). While the correlations only partially confirmed links between resting baseline HRV, well- and ill-being in the current small sample, all significant results were in the expected directions, and these findings are broadly consistent with the literature indicating that people with greater well-being have higher resting HRV, while those suffering from ill-being have lower HRV.

4.2. Time effects of Vipassana training on HRV

Contrary to our hypotheses, there were no significant main effects of time, overall across tasks, after 10 days of intensive Vipassana training. Changes in HRV over time have not been well characterised for mindfulness meditation, so it is possible that there were simply no effects to find. Changes in resting baseline HRV over time have, however, been found with less intensive mindfulness meditation training (Tang et al., 2009). This result suggests that either there are important differences between Vipassana and the mindfulness intervention used by Tang et al., or that the sample in the current experiment was too heterogeneous or insufficient in size for us to detect changes in HRV after Vipassana training, compared to before.

4.3. Task effects of meditation on HRV

The effects of the meditation task on HRV were not entirely as expected, although the hypothesis was partly borne out. Absolute HF power (ln HF) did increase as expected in the meditation task compared to resting baseline, while HF n.u. was in the expected direction but failed to reach significance. These results are interpreted below in the context of the interaction effects.

4.4. Interactions of meditation time and task effects on HRV

Of the HRV measures, the overall interactions were significant only for THM, while absolute HF only approached significance despite the large effect size. There were, however, interesting and unexpected differences in between the meditation task and resting baseline, considering pre- and post-Vipassana measures separately. Absolute HF power increased in the meditation task (as indicated by the main effect of task), but only before Vipassana training. Normalised HF increased and THM decreased in the meditation task compared to resting baseline only after Vipassana training.

4.5. Patterns of HRV changes

The interpretation of the post-Vipassana resting baseline is extremely interesting, as HF n.u. increased in line with prior meditation studies (e.g. Wu and Lo, 2008), but the rest of the data defies a simple

explanation concerning straightforward increases in sympathovagal balance. As a ratio, increases in normalised HF can be driven either by increases in overall HF power or by decreases in LF power (as observed in our results). The profound loss in THM power around the frequency of the baroreflex explains both the trends towards decreased measures of total power, and the significant increase in HF n.u. in the absence of any change in absolute HF. While this is not straightforward to interpret, an intriguing possibility presents itself.

Firstly, loss of power in the baroreflex-mediated HRV has been classically associated with mental effort or stress (see van Roon et al., 2004). However, this does not confine itself to unpleasant experiences, and could be triggered by an interesting, engaging, demanding or stressful task. This loss in baroreflex power appears to be related to attentional load (i.e. Mulder and Mulder, 1981) independent on the valence of that load.

In this respect, mental load is reminiscent of the concept of 'flow' — a state of positive and full immersion in an activity (Csíkszentmihályi, 1996). Indeed, some studies directly attempting to measure flow have reported the same reduction in LF power or equivalent to classical studies on attentional load and the result here. For instance, Keller et al. (2011) reported a reduction in time-domain HRV which was greater in an engaging task than one of either little or great difficulty. This suggestion does not contradict the increased LF results in breathing meditation reported for example by Lehrer et al. (1999). Slow breathing has very powerful effects on LF power, and would be likely to overwhelm changes in resting baseline caused by immersion in the meditation. It is also worth noting that de Manzano et al. (2010), reported quite different results to Keller et al., positive correlations between self-reported flow and LF/HF ratio, and negative correlations between flow and RSA, in a small sample of musicians.

The possible relations with flow posit a different role for meditation task effects in this context. Rather than the meditation task immediately enhancing vagal tone (leading to an increase in HF n.u.), it lowers LF power through focused, pleasurable attention (likewise leading to an increase in HF n.u.). In the light of this possible explanation, the interactions between acute meditation task effects and intensive Vipassana meditation training could be interpreted as follows. Before meditation training, participants asked to focus on breathing actually alter their respiration patterns, driving up ln HF power. After the intensive Vipassana intervention, participants are capable of becoming immersed in attending to their breathing without profound alterations in respiration, and this engaging task decreases measures of LF power.

4.6. Limitations and future directions

There are several limitations of the present study, and interpretations should be considered preliminary for several reasons. Firstly, this is a small sample of data, collected outside of laboratory conditions, which may have contributed to the unfortunately large proportion of participants who had to be excluded due to errors in HRV data. The design was also exploratory, which required multiple measures without correction for family-wise error. The within-subjects design also did not involve a control group and thus leaves open issues of self-selection bias in the sample. These results need to be replicated utilising a between subjects design. Properly controlled, blinded and randomised between subjects trials are rare in meditation research (Ospina et al., 2007) as they are difficult to design and run. However such studies are needed to confirm results of preliminary within-subject trials.

Finally, there was no direct control for respiration during the experimental observations. Despite the importance of respiratory sinus arrhythmia in HRV, controlling for respiration is far from routine in HRV studies. Indeed Denver et al (2007) question the need to manipulate or monitor respiration in order to generate an accurate measure of RSA, and point out that methods of correcting HRV measures for respiration are inconsistent and problematic. Direct measures of respiration would have been useful in order to rule out profound changes in respiration depth and frequency of the sort reported in experienced Zen meditators (Lehrer et al., 1999), however they were not essential for the results of the current study to make a meaningful contribution to the literature.

The Vipassana intervention studied here, while including mindfulness of breathing, does not incorporate the sort of deliberately paced slow breathing that is an integral part of many of the Zen practices studied in the literature, in which profound changes in breathing occur. While awareness of respiration is indeed an important element in Vipassana meditation, control of respiration is not. This is particularly reinforced by the fact that we observed task related decreases in THM, a component of LF HRV associated with baroreflex output. This is opposite to the HRV findings associated with profound breathing changes associated with meditation, and strongly suggests that the findings of the current study were not due to respiration changes post-Vipassana. In addition, even in studies of breathing-focused meditation, it has been demonstrated that the effects of meditation, even including strongly paced breathing, cannot be reduced to respiration changes alone (Murata et al., 2004; Takahashi et al., 2005). Although a planned comparison, the effect for normalised HF should be treated with caution, given the lack of significant interaction. This result is nevertheless of interest, given the change in absolute measures and the prior research into the effects of meditation on normalised HF.

These results require replication in a larger sample with the addition of direct respiration measures in order to be confident of the proposed interpretation. The results do, however, illustrate the need to examine a well-chosen array of HRV frequency variables, rather than single measures in isolation.

4.7. Conclusion

Overall, the effects of meditation on well-being and ill-being were consistent with expectations; the results of the self-report measures suggest that Vipassana mediation had a pronounced positive psychological effect on the participants. Cardiovascular results, however, were more complex. After meditation training, the meditation task increased normalised HF HRV, as is common for mindfulness meditation tasks without paced breathing. While the pattern of results for other HRV measures did not accord neatly with our expectations, results provide a useful insight into the nature of ANS function during and following Vipassana meditation.

While increases in normalised HF power such as often observed in meditation studies can and have been interpreted as increases in parasympathetic activity, the addition of absolute HF and LF power measures revealed that the driving force behind the normalised HF changes in this sample was more likely a decrease in LF rather than an increase in HF power. Importantly, decreases in the low-frequency spectrum of HRV may underpin increases in normalised HF – as we show here – highlighting the need for the addition of absolute frequency-based measures in order to interpret changes in normalised units.

While it is possible that these differences represent differences between meditation styles, we suggest that these changes in the meditation task may be related to the concept of 'flow,' a state of positive, effortful immersion in an activity. The results require replication in a larger sample under more controlled conditions in order to properly characterise the effects of meditation.

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