MEANING IN LIFE:
CARDIAC-VAGAL AND TIME-VARYING PROPERTIES DURING REST, STRESS, AND MINDFULNESS

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Abstract

Background. Higher meaning in life (MIL) consistently predicts better health, but the physiological processes underlying this relationship are not well understood. Additionally, while MIL is theoretically supported as a state variable, few studies have investigated its state-like variability.

Method. This study examined the relationship between MIL and vagally-mediated heart rate variability (VmHRV) under resting (*N* = 77), stressor (*n* = 73), and mindfulness intervention (*n* = 72) conditions. As a secondary question, this study investigated the modifiability of state MIL via experimental exposure. Regression was used for MIL-VmHRV analyses at baseline, and longitudinal mixed models were used to examine phasic changes in (a) VmHRV as a function of MIL and (b) state MIL.

Results. Regression analyses revealed a quadratic baseline MIL-VmHRV relationship, and mixed models linked higher MIL to greater stress-reactivity but not enhanced stress-attenuation. MIL and MM did not interact to influence VmHRV recovery after experimental stress. State MIL was lower after stress relative to baseline, higher after intervention relative to stress, and higher after intervention relative to baseline.

Conclusion. Findings suggest that cardiac vagal tone and cardiac vagal reactivity are linked to MIL, and that MIL fluctuates even within brief timeframes. Future research is needed to further clarify the physiology of MIL and the extent to which brief interventions can influence life meaning.

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1. Introduction

1.1. Rationale

Promoting psychological resilience is a recognized global priority. Almost a million die by suicide annually (World Health Organization, 2014) and roughly a billion live with mental illness (MI) every day (James et al., 2018; Ritchie & Roser, 2018). People with MI are at greater risk of premature death (Walker et al., 2015), with reductions in life expectancy approaching 24 years (Chesney et al., 2014). In terms of functional years lost, MI is associated with a burden 1.5 times greater than all cancer burdens combined and 7 times greater than the total burden of all infectious diseases (Ratnasingham et al., 2012). MI continues to be a leading cause of disability worldwide (Whiteford et al., 2013), and in Canada, the yearly economic burden due to healthcare, lost productivity, and other costs is estimated at $50 billion and projected to increase six-fold by year 2041 (Mental Health Commission of Canada, 2013). The consequences of MI underscore the urgent need for continued intervention innovation.

Despite the advances of psychiatry in treating MI, preoccupation with the medical model has led to rejections of non-biological perspectives that could lead to further advances (Sedler, 2016). Critics argue that this "one-dimensional psychiatry" contributes to a narrow view of suffering and excess pharmacotherapy (Frances, 2013; Paris, 2015; Sedler, 2016), in turn, reducing the self-efficacy and self-responsibility integral to sustained patient recovery (Breggin, 2003). A more inclusive view of psychology and suffering may stimulate progress (Ghaemi, 2007; B. Lewis, 2011; Peters et al., 2012; Schwartz et al., 2017; Sedler, 2016), especially in the domain of *meaning in life* (MIL).

MIL is widely viewed as a central motivating experience that improves psychotherapeutic outcomes (Debats, 1996; Vos et al., 2015), reduces symptoms (Corona et al., 2019), protects against disease (R. Cohen et al., 2016), and supports health across the life span (Czekierda et al., 2017). One way MIL may confer health is by promoting resilience in the face of stress and adversity (Frankl, 1963; Wong, 2012). Given obvious clinical implications, MIL has stimulated considerable empirical interest (Roepke et

al., 2013; Steger, 2018), with research into its biological concomitants illuminating pathways from meaning to health (Ryff, 2012). Yet, despite current scientific efforts, little is understood about MIL's physiological basis (Hooker et al., 2018), especially under stressful conditions. In this thesis, MIL is assessed in terms of autonomic regulation via heart rate variability (HRV), a reliable marker of health status and regulated biological functioning.

MIL's associations with good health also highlights the importance of identifying methods that enhance MIL. Recent theory suggests that mindfulness meditation may play such a role (Garland et al., 2015). Relatedly, other investigators suggest that MIL has state variable characteristics (Frankl, 1963, p. 131). Thus, the present research additionally assesses whether MIL has state-like modifiability under conditions of stress and stress-reduction.

1.2. Objectives

This thesis aims to clarify (1) the relationship between MIL and HRV under resting, stressful, and mindfulness-recovery conditions, and (2) whether these conditions are associated with MIL state changes. Studying MIL from a physiological perspective provides a biological basis for existential thought in clinical practice. If MIL is indeed a resilience factor grounded in biopsychological science, patients may benefit from more of a focus on MIL in psychiatry and related medical fields.

2. Literature Review

2.1. HRV: Physiological Foundations

HRV provides a measure of functional status in the autonomic nervous system (ANS; Acharya et al., 2006; Karim et al., 2011) that relates to interaction between its two branches: the sympathetic nervous system (SNS) and the parasympathetic nervous system (PNS). The SNS mobilizes energy to support fight-or-flight behaviors under perceived threat and challenge, whereas the parasympathetic branch – notably served by the vagus nerve (cranial nerve X) – promotes homeostatic conditions essential for health and restoration (Porges, 2011). The heart is innervated by both ANS branches, which modulate heart rate via the sinoatrial (SA) node, the heart's natural pacemaker (Pumprla et al., 2002). When sympathetic nerve fibers release norepinephrine on the SA node, the heart contracts at a quicker rate, and when acetylcholine is released by parasympathetic nerve fibers, the heart contracts more slowly (Berntson et al., 1997). Norepinrephrine's effects on cardiac activity occur slowly, peaking at about 4 s and returning to baseline within 20 s (Appelhans & Luecken, 2006). By contrast, acetylcholine influence has a faster time course that peaks at approximately 0.5 s and returns to baseline within 1 s (Appelhans & Luecken, 2006). Consequently, parasympathetic influences are relatively instantaneous, enabling heartbeat changes that covary with respiration in a phenomenon called respiratory sinus arrhythmia (Appelhans & Luecken, 2006; Pumprla et al., 2002). Specifically, during inhalation, parasympathetic control over cardiac function is temporarily gated and increases heart rate, whereas during exhalation, parasympathetic control is restored and reduces heart rate (Appelhans & Luecken, 2006). HRV is derived from these heartbeat variations over time, providing an index of parasympathetic activity via vagus nerve activity (Task Force, 1996). It should be noted that although certain HRV measures reflect other physiological influences, those that assess parasympathetic activity specifically have the firmest theoretical foundations (Laborde et al., 2017) and are most relevant for the present study. The term vagally-mediated HRV (VmHRV) will be used to refer to these measures.

High VmHRV is generally a sign of cardiac health, reflecting the ANS's ability to respond dynamically and efficiently to stimuli (Acharya et al., 2006; Thayer et al., 2010), though recent work has also shown that very high VmHRV levels may indicate maladaptive processes (Kogan et al., 2013). Low VmHRV, by contrast, signals autonomic inflexibility and dysregulation, a pattern linked to a variety of suboptimal and pathological conditions (Thayer & Brosschot, 2005) including prolonged stress reactivity (Brosschot et al., 2007), impaired allostatic recovery (C. S. Weber et al., 2010), physical disease (Task Force, 1996), and psychological dysfunction (Beauchaine & Thayer, 2015). Of particular relevance is the established link between VmHRV and adaptive functioning, which is conceptually rooted in two neurophysiologically-based theories: polyvagal theory and the neurovisceral integration model.

2.1.1. Polyvagal Theory: VmHRV and Social Functioning

The vagus nerve is the longest cranial nerve, connecting brainstem regions to multiple organs as it travels through the body to the colon (Câmara & Griessenauer, 2015). "Polyvagal" refers to the two phylogenetically distinct vagal branches and their different functions (Porges, 2011). The older, unmyelinated branch triggers metabolic shutdown (e.g., immobilization and freezing) in response to extreme stress, whereas the newer, myelinated vagus acts as an autonomic "brake", inhibiting the defense mechanisms of the SNS in favor of behavioral states essential for social engagement (e.g., intimacy, social play, and interpersonal communication; Porges, 2011).

According to polyvagal theory, the newer vagus forms a "social engagement system" that joins somatomotor (striated muscles of head and face) and autonomic components in a "face–heart connection" that supports or impedes social bonding (Porges, 2001, 2007, 2011). Threatening facial expressions for example, trigger autonomic defenses incompatible with social engagement, while vagally regulated autonomic states support calmer expressions and pro-sociability (Porges, 2003, 2018).

VmHRV indexes activity in the newer vagus, and by association, the capacity for adaptive social behaviors (Di Bello et al., 2020; Porges & Furman, 2011). Indeed, considerable evidence suggests that

higher resting VmHRV (cardiac vagal tone) is associated with aspects of positive social functioning such as social integration and acceptance (Geisler et al., 2013), social competence in young boys (Eisenberg et al., 1995), expressions of sympathy in children viewing other children in distress (Fabes et al., 1993), better marital quality (T. W. Smith et al., 2011), and longitudinal increases in social connectedness (Kok & Fredrickson, 2010).

2.1.2. Neurovisceral Integration Model: VmHRV and Self-Regulation

According to the neurovisceral integration model (NIM), VmHRV is linked to aspects of self-regulation associated with the central autonomic network (CAN; R. Smith et al., 2017; Thayer et al., 2009), a control network of reciprocally connected neural regions that coordinate physiological mechanisms with cognitive-affective responses essential for adaptation and purposeful behavior (Benarroch, 1993). A central assumption of NIM is that within the CAN, prefrontal cortical (PFC) regions exert tonic inhibitory control on subcortical regions associated with threat appraisal such as the amygdala (Heatherton & Wagner, 2011; Thayer et al., 2009; Thayer & Lane, 2000). Under perceived stress or threat, PFC inhibition is withdrawn and subcortical sympathoexcitatory structures are disinhibited to support defensive responses (G. Park & Thayer, 2014; Thayer et al., 2012). While adaptive when context-appropriate, inefficiency and prolonged disruption in this inhibitory pathway results in dysfunctional states such as hyper-vigilance, rigid attentional processing, and perseverative cognition (rumination and excessive worry; Brosschot et al., 2006, 2007; Thayer et al., 2012). The CAN and its ability to modulate the time course of stress responses via inhibitory processes is therefore critical for self-regulation and behavioral flexibility (Appelhans & Luecken, 2006; Heatherton & Wagner, 2011; R. Smith et al., 2017). Because CAN output reaches the heart via sympathetic-vagal innervation, a primary NIM hypothesis is that VmHRV reflects functional connectivity in prefrontal-subcortical circuits and related self-regulatory functions (R. Smith et al., 2017; Thayer & Lane, 2000). Supporting these assumptions is a large evidence base linking higher VmHRV to higher executive functioning (Thayer et

al., 2009), better regulated emotional responding (Appelhans & Luecken, 2006), and neuroimaging indications of greater PFC activity (Thayer et al., 2012).

2.1.3. VmHRV and Health

As an index of adaptive functioning, VmHRV is associated with a wide range of health processes and outcomes. Physically, reduced VmHRV is predictive of cardiovascular disease (Task Force, 1996), greater mortality risk following myocardial infarction (Carney et al., 2001), diabetes (Schroeder et al., 2005), and hypertension (Schroeder et al., 2003), amongst other morbidities (Thayer et al., 2010).

In many of these diseased states, excessive homeostatic disruption (lower resting VmHRV) caused by chronic stress is thought to be a common risk factor. Indeed, findings link mental stress (H. G. Kim et al., 2018), work stress (Jarczok et al., 2013, 2020), and stress vulnerability (Brosschot et al., 2006, 2007) to lower VmHRV, and lower VmHRV to elevated risk among various biomarkers (Jarczok et al., 2019) and allostatic processes (Thayer & Sternberg, 2006), as well as impaired recovery of allostatic systems following psychological stress (C. S. Weber et al., 2010).

Psychologically, lower VmHRV is correlated with various dysfunctions, particularly depression, anxiety, poor executive control (Beauchaine & Thayer, 2015), maladaptive perfectionism (Azam et al., 2015), post-traumatic stress disorder (Tan et al., 2011), borderline personality disorder (Koenig et al., 2016), and suicidality (Forkmann et al., 2016; Tsypes et al., 2017).

A common feature of many mental disorders is emotional dysregulation linked to chronic ANS imbalance (i.e., low VmHRV; Beauchaine, 2015; Thayer & Brosschot, 2005). Indeed, lower resting VmHRV predicts hypervigilance in response to threat (Miskovic & Schmidt, 2010), greater fear-related startle (Gorka et al., 2013; Wendt et al., 2015), slower safety learning (Pappens et al., 2014), and higher self-rated distress during periods of high-stress (Gouin et al., 2014). By contrast, higher baseline VmHRV is linked to greater spontaneous use of adaptive emotion regulation strategies (e.g., cognitive

reappraisal; Volokhov & Demaree, 2010) and reduced use of spontaneous avoidance (a maladaptive strategy) in response to unpleasant stimuli (Aldao et al., 2016).

Consistent with NIM, higher resting VmHRV is positively associated with various executive functions supportive of self-regulation such as cognitive flexibility (task shifting; Colzato et al., 2018), inhibitory control (ability to inhibit dominant behavioral responses; Ottaviani et al., 2019), ability to control unwanted memories (Gillie et al., 2014), and working memory (a core executive function; Hansen et al., 2003). VmHRV is thus broadly supported as a reliable measure of self-regulated responding across a variety of contexts related to health and wellbeing.

Unsurprisingly, given associations with self-regulatory control, VmHRV also correlates positively with healthy behaviors and lifestyle factors. For example, alcohol consumption (Quintana et al., 2013; Reed et al., 1999), greater trans-fat intake (Soares-Miranda et al., 2012), and less control over one's eating (disinhibited eating; Young & Watkins, 2016) are correlated with lower VmHRV, whereas higher VmHRV is associated with smoking cessation (Minami et al., 1999), aerobic training (Hautala et al., 2009; Prinsloo et al., 2014; Sandercock et al., 2005), better sleep quality (Werner et al., 2015), and diets typically associated with health (e.g., Mediterranean [Dai et al., 2010] and vegetarian [Fu et al., 2006] diets).

Given its ability to index numerous pathways to health and disease, VmHRV may also relate to individual differences in meaning in life.

2.2. What is Meaning in Life?

Meaning in life (MIL) is distinct from meaning *of* life: The latter poses metaphysical questions aimed at understanding the significance of the universe and the function of life (e.g., "Why are we here?" and "What is the purpose of life?"; Martela & Steger, 2016), whereas MIL is a subjective concern about "What makes *my* life worth living?" (Debats et al., 1995).

Operational definitions of MIL revolve around three central concepts: *coherence*, *purpose*, and *significance* (King & Hicks, 2021). *Coherence* is observed when people comprehend and make sense of informative patterns. *Purpose* is associated with systematically-derived goals and directions, and *significance* is associated with perceiving actions as consequential and life as valuable (George & Park, 2016; Martela & Steger, 2016). Deficits in these characteristics (i.e., a life low in meaning) are hypothesized to result from *inabilities* to see value in life, resulting in boredom, indifferent decision-making, and low expenditures of effort (Maddi, 1967).

2.2.1. Meaning and Health

The emphasis on studying MIL (Steger et al., 2006) is consistently reinforced by associations between higher meaning and better health outcomes, from improved measures of mental wellbeing including more self-acceptance (Steger, Kashdan, Sullivan, et al., 2008), enhanced psychological resilience (M. C. Weber et al., 2020), and reduced suicidal ideation (Heisel et al., 2016) to healthier physical outcomes such as lower cardiovascular risk (E. S. Kim et al., 2013), reduced risk of disability (Boyle, Buchman, & Bennett, 2010), and improved life expectancy (Boyle et al., 2009; Krause, 2009). Advances in psychobiology also link higher MIL to healthier biomarker patterns including reduced levels of soluble IL-6 receptor (an inflammatory factor; Friedman et al., 2007), higher HDL cholesterol (a cardioprotective factor; Ryff et al., 2004), increased telomerase activity (an enzyme linked with longevity; Jacobs et al., 2011), and lower allostatic load 10 years later (Zilioli et al., 2015).

Despite research on MIL and health indicators, there is insufficient data on how MIL manifests physiologically, especially in terms of its predictive relationship with stress-reactivity and recovery. However, several hypothesized pathways underlying the MIL-health relationship point to VmHRV as a likely marker of MIL.

2.2.2. Meaning and Relationships

One pathway involves social relationships, as close relationships are a central source of MIL and support all three MIL characteristics (Debats, 1999; King & Hicks, 2021). Moreover, MIL and social connectedness likely interact in cycles where close relationships elevate MIL and elevated MIL promotes social bonding (Stavrova & Luhmann, 2016). In particular, those with higher MIL have more interpersonal appeal and form relationships more easily (Stillman & Lambert, 2013), aligning with evidence that higher MIL also predicts marriage, community engagement, and social connectedness years later (Stavrova & Luhmann, 2016). Individuals with higher MIL may therefore have greater access to the health-promoting (S. Cohen, 2004; Umberson & Karas Montez, 2010) and self-regulatory (Fitzsimons & Finkel, 2010; Skerrett & Fergus, 2015) benefits of positive relationships, which, given the interpersonal neurobiological foundations of polyvagal theory, support VmHRV's relevance as a likely concomitant of MIL.

2.2.3. Meaning and Executive Control

Purposeful living involves skillful deployment of resources to purpose-relevant goals, behavioral inhibition when faced with goal-conflicting desires, and greater psychological flexibility when obstacles endanger goal-fulfillment (N. A. Lewis, 2020; McKnight & Kashdan, 2009). Correspondingly, executive functions (EFs) support planning and goal-oriented behaviors, inhibitory control over prepotent responses, and adaptive responding when contingencies require relinquishing old ideas in favour of novel ideas (Suchy, 2016; P. G. Williams et al., 2017). It is therefore reasonable to expect an association between a sense of life purpose and EFs. Indeed, a positive relationship has been demonstrated in a large sample (N. A. Lewis et al., 2017). Multi-year studies have also shown that higher purpose predicts better baseline and subsequent working memory (a core EF; Boyle, Buchman, Barnes, et al., 2010; Wilson et al., 2013). Accordingly, other longitudinal work has demonstrated via brain autopsy and cognitive assessment (including EF testing) that higher life purpose reduced the association between Alzheimer's pathology (e.g., neuritic plaque and neurofibrillary tangles) and cognitive decline (Boyle et

al., 2012). Not surprisingly, higher purpose in life is associated with greater perceived self-control (Li et al., 2019) and less impulsivity (measured via a delayed discounting task; (Burrow & Spreng, 2016). Likewise, experimentally induced MIL also appears to enhance inhibitory control in relation to addictive behaviors (Ostafin & Feyel, 2019). Altogether, given well-established positive associations between EFs and health (P. G. Williams et al., 2017), another pathway by which MIL confers better health likely involves enhanced executive functioning (N. A. Lewis et al., 2017), which has obvious theoretical overlap with the prefrontal cortical underpinnings of VmHRV.

2.2.4. Meaning and Health Behaviors

The view that a sense of purpose and "mattering" in the world promotes health behaviors and reduces risky behaviors (Hooker et al., 2018; Steger et al., 2015) is well summarized by the notion that "taking good care of oneself in … daily health practices presupposes a life … worth taking care of" (Ryff & Singer, 1998, p. 22). Indeed, Hooker and Masters (2018) found that those more aware of what gave their lives meaning exercised for greater durations and at higher intensities. Similarly, using accelerometers to objectively measure physical movement, Hooker and Masters (2016) found that individuals with greater life purpose engaged not only in more physical activity, but also in more physically vigorous activity. Additionally, Zilioli et al. (2015) demonstrated that individuals with more purpose in life believed more in their control over their health, which partially explained their lower allostatic loads a decade later. These findings parallel other work (E. S. Kim et al., 2014) showing that greater life purpose predicts greater use of preventative health care services. Conversely, Steger et al. (2015) demonstrated that lower MIL predicted increased substance use, more health-risking attitudes, and increased health symptoms. Given the body of work linking VmHRV to healthy lifestyle choices, these findings further support VmHRV as a likely marker of a MIL.

2.2.5. Meaning and Stress-Regulation

Existing data suggest higher MIL buffers adverse life stress (E. S. Kim et al., 2019), leading to assertions that when people experience uncontrollable stressors, *coherence* can improve self-regulation by increasing the comprehension of stressors that would otherwise appear random (Hooker et al., 2018; J. Park & Baumeister, 2017). Additionally, enhanced experiences of *life purpose* appear to attenuate stress-reactivity by providing a framework where goals and associated cognitions are coherently organized, facilitating adaptive prioritizing of daily stressors (Halama, 2014; McKnight & Kashdan, 2009).

Several studies support these assertions, with greater life purpose linked to quicker emotional recoveries (reflected in smaller eyeblink reactions; Schaefer et al., 2013), fewer emotional difficulties among caregivers (Polenick et al., 2018), reduced activation of the amygdala (a region linked to fear and anxiety-related emotions; Van Reekum et al., 2007), and more ventral anterior cingulate cortical activity (linked to amygdala down-regulation; Van Reekum et al., 2007). Conversely, induced meaninglessness appears to increase stress perceptions during stress induction protocols (J. Park & Baumeister, 2017).

The studies cited above suggest the stress-buffering of higher MIL relates to increased proactive coping (Halama, 2014; Hooker et al., 2018; Miao & Gan, 2019), problem-focused coping (Skrabski et al., 2005), and emotional-focused coping (Marty et al., 2010). In turn, higher MIL is linked with greater self-efficacy (Skrabski et al., 2005), reflected in studies of loss and illness that demonstrate associations between higher MIL and improved psychological adjustment such as lower levels of grief-related distress after losing a loved one (Edmonds & Hooker, 1992) and more positive reappraisals in patients diagnosed with congestive heart failure (C. L. Park et al., 2008). If MIL indeed attenuates stress-reactivity and stress perceptions (E. S. Kim et al., 2019), individual MIL differences should manifest in cardiac vagal control and VmHRV measures.

2.2.6. Meaning and Mindfulness-Based Recovery

Given faster rates of emotional recovery associated with MIL (Schaefer et al., 2013), a relevant question is whether stress-reduction interventions may further accelerate recovery as a function of MIL.

One such intervention is mindfulness meditation (MM), a form of awareness training with demonstrated success in facilitating parasympathetic dominance (Burg et al., 2012; Ditto et al., 2006; Krygier et al., 2013) and parasympathetic recovery after stress (Azam et al., 2015, 2016).

Conceptually, mindfulness refers to a conscious awareness of events and experiences occurring in the present moment (K. W. Brown et al., 2007). While many types of MM exist, most promote states of relative calm through non-judgmental, deliberate attention to cognitions, emotions, and sensations (Didonna, 2009). Importantly, mindfulness training typically involves moment-to-moment monitoring and returning attention to the present when the mind has wandered (Teper & Inzlicht, 2013). As such, MM requires executive control, which indeed, appears to improve after MM practice (e.g., improved prefrontal control, anterior cingulate cortical activity, and cognitive inhibition; for reviews see Gallant, 2016; Jankowski & Holas, 2014; Teper et al., 2013).

Given positive linkages between MIL and executive functioning (N. A. Lewis, 2020), those with higher MIL may be more able to meet the attentional demands of MM practice and in turn access more of its stress-reducing benefits.

2.3. Primary Research Question

The present study examines whether higher vs. lower MIL uniquely predicts cardiac vagal control under resting, stress, and recovery conditions while controlling for depression symptoms[1] and positive affect, potential mood confounders known to correlate with both MIL (King et al., 2006; Steger et al., 2006) and VmHRV (Kemp et al., 2010; Oveis et al., 2009).

[1] The decision to control for depression symptoms instead of negative affect was guided by evidence that depression is more strongly associated with MIL (Steger et al., 2009, p. 50; Steger & Kashdan, 2013, p. 107).

2.3.1. Hypothesis 1

Greater MIL will be associated with greater levels of VmHRV during resting baseline. Only two known studies (Ishida & Okada, 2006; Sloan et al., 2017) have addressed this question. Although neither revealed a baseline relationship,

- Ishida and Okada's (2006) analysis relied on (1) Crumbaugh and Maholick's (1964) Purpose in Life test, which has been criticized for conflating purpose with additional factors of mood, depression, zest, and enjoyment (Heintzelman & King, 2014; Steger, 2006; Steger et al., 2006) and (2) variable dichotomization, which introduces a host of statistical issues (e.g., lost ability to detect non-linear relationships; Royston et al., 2006),
- whereas Sloan et al.'s (2017) findings suffer from a substantial time lag (864 ± 427 days) between the collection of psychological measures and VmHRV data.

2.3.2. Hypothesis 2

Higher MIL will relate to (a) less stress reactivity (smaller VmHRV reductions) in response to an artificial stressor and (b) faster stress attenuation (more cardiac vagal input) as the artificial stressor progresses. Guiding this hypothesis are views of MIL as a stress-buffer and VmHRV as an index of self-regulatory capacity. The only known study (Ishida & Okada, 2006) to directly examine this question found greater HRV indications of stress reactivity among low life purpose individuals during a 5-min stressor. This study extends previous work by examining minute-by-minute changes in stress responding as measured by VmHRV.

2.3.3. Hypothesis 3

Higher MIL will interact with mindfulness meditation (MM) to accelerate parasympathetic recovery after stress induction. More specifically, an “active” MM condition employing guided instruction will facilitate faster VmHRV recovery in individuals with higher MIL compared to a “control” MM condition devoid of relevant instruction.

2.4. Mindfulness Meditation: A Catalyst for Meaning

A related question is whether MM can deepen one's sense of MIL in the face of stress. Although this effect is often observed in clinical settings (Carlson, 2015), empirical verification is limited. Recently however, researchers have articulated a process (mindfulness-to-meaning theory [MMT]; Garland et al., 2015; Garland & Fredrickson, 2019) by which MM may strengthen the ability to derive meaning from adverse life events. According to MMT, non-evaluative attention creates psychological distance from mental stress (decentering) and broadens meta-cognitive awareness. Once disengaged from negative cognitive automaticity, positive affective tone emerges, enabling positive reappraisals, positive emotions, and ultimately, a deepened sense of MIL (Garland et al., 2015).

Only two known studies have investigated the link from MM to MIL. One study examined the benefits of loving-kindness meditation, a technique aimed at cultivating cognitive-affective states of good-will for self and others, and found that over the course of nine weeks, loving-kindness meditation practice amplified positive affect, which in turn led to increased purpose in life (Fredrickson et al., 2008). Another study (Jacobs et al., 2011) examined pre-post psychometric changes linked to an intensive, three-month meditation retreat, and found that meditators reported a greater sense of purpose compared to baseline and wait-list controls.

2.5. Secondary Research Question

The present study aims to extend the above findings by investigating the impact of MM on MIL following a stressful experience. Importantly, this investigation reconceptualizes MIL as a potential state-like variable that continually changes "from day to day and from hour to hour" (Frankl, 1963, p. 131). Viewing MIL as such helpfully reframes problems of meaninglessness as potentially resolvable within pragmatic, here-and-now timeframes. To this end, the present study employs a novel measure adapted to capture state fluctuations in MIL following stress and MM.

2.5.1. Hypothesis 4

MIL will be depend on experimental exposure: State MIL will (a) decrease from baseline to post-stress, (b) increase faster from post-stress to post-treatment in the “active” MM condition relative to the “control” MM condition, and (c) increase from baseline to post-treatment.

3. Method

3.1. Participants

Study participants were between the ages of 17-27 years. Participants were recruited through an undergraduate research pool that grants university course credit for participation. Exclusion criteria included diabetes, cardiovascular diseases (arrhythmias and hypertension), and psychiatric illnesses (e.g., anxiety, depressive, and eating disorders), as their association with VmHRV is well-documented. This study was approved by the Human Participants Review Committee at York University.

3.1.1. Sample Size Estimation

Based on an a-priori power analysis (G*Power 3.1) and a randomized control trial design for testing MM's effect on VmHRV, a sample of $N = 52$ was estimated to provide adequate power ($1 - \beta = .80$) for detecting a medium (Burg et al., 2012) to large (Krygier et al., 2013) effect ($f^2 = 0.20$) based on $\alpha = .05$. Further assuming a 20% drop-out rate, it was estimated that $N = 65$ would be an appropriate sample size. Stoppage of data collection was informed by this sample estimation and determined by COVID-19 pandemic restrictions.

3.2. Measures

3.2.1. VmHRV: RMSSD and HF-HRV

VmHRV was acquired using a 3-lead electrocardiogram (ECG) configuration attached to both wrists and the left ankle. ECG signals were digitized using a PowerLab 4/35 acquisition system (ADInstruments, Colorado Springs, United States) at a sampling rate of 1000 Hz. Digitized signals were recorded and analyzed using LabChart 8 software. Labchart 8's HRV 2.0 module was used for R wave detection and VmHRV analysis. Prior to analysis, all ECG recordings were visually inspected for artifacts, arrhythmias, and ectopic beats, and manually adjusted if beat markers were missing or misplaced. VmHRV was calculated from spectral analysis in the high frequency band (0.15–0.40 Hz [HF-HRV]) using the Lomb-Scargle Periodogram algorithm and from time domain analysis of the root mean square of

successive heart beat differences (RMSSD). RMSSD and HF-HRV are strongly correlated (Laborde et al., 2017) and are preferred measures of VmHRV (Task Force, 1996). 5-min measurements of RMSSD and HF-HRV were used for cross-sectional analyses (Hypothesis 1), and because RMSSD yields valid estimates even from ultra-brief recordings (e.g., 1 min; Esco & Flatt, 2014; Melo et al., 2018; Nussinovitch et al., 2011; Shaffer et al., 2016), RMSSD was used to assess longitudinal change (slopes and trajectories) on a minute-to-minute basis (Hypotheses 2-3).

3.2.2. Respiratory Frequency

There is ongoing debate about whether VmHRV should be adjusted for respiratory parameters. Some researchers argue that adjustment is needed to accurately assess VmHRV (Grossman & Taylor, 2007), whereas others argue that respiration and VmHRV share a common genetic-neural origin and that removal of respiratory-related variance inappropriately removes some of the influence from this common origin on heartbeat, in turn, eliminating important individual differences (for a detailed review see Thayer et al., 2011). Therefore, respiratory frequency was included as a time-varying covariate to supplement primary findings. Respiration data were acquired using a TN1132/ST respiratory belt (ADInstruments, Colorado Springs, United States) positioned over the diaphragm at the area of maximum respiratory expansion.

3.2.3. Meaning in Life Questionnaire (MLQ)

The presence of meaning subscale (MLQ-P) (Steger et al., 2006) was used to measure the degree of overall MIL perceived by participants at baseline. The MLQ avoids presupposing any one definition of meaning and instead, allows respondents to define "meaning" for themselves (Steger et al., 2006). Participants rated the MLQ-P's five items using a 7-point scale ranging from "strongly disagree" to "strongly agree". The MLQ-P has demonstrated good internal consistency (Cronbach's alpha = .82), test-retest reliability, and convergent and divergent validity (Steger et al., 2006).

3.2.4. Meaning in Life – State Scale (MIL-S)

The MIL-S consists of five items used to measure state MIL at baseline, post-stress, and post-treatment. Because no known measure of state MIL exists, items were primarily adopted from validated scales (Thoughts of Meaning scale, Hooker & Masters, 2018; MLQ-P, Steger et al., 2006; Daily Meaning scale, Steger, Kashdan, & Oishi, 2008) and converted to their state equivalent. Participants were asked to rate their feelings "right now" about items that measure coherence (e.g., "Right now, life makes sense"), purpose (e.g., "Right now, my activities feel consistent with my life goals and purpose in life"), and significance (e.g., "Right now, my life feels worthwhile"). Participants rated each item using a 4-point Likert scale (1 = not at all; 2 = a little; 3 = a good deal; 4 = very much so).

3.2.5. Positive and Negative Affect Schedule (PANAS)

The positive affect subscale of the PANAS (PANAS-P; Watson, Clark, & Tellegen, 1988) was used to assess positive affect at baseline and incorporated as a covariate in all primary analyses. The PANAS-P consists of 10 adjectives that describe positive affect (e.g., interested, enthusiastic, and strong). Participants rated the extent to which they felt each adjective during the past week using a 5-point Likert scale ranging from 1 ("very slightly or not at all") to 5 ("extremely"). The PANAS has demonstrated internal consistency (Cronbach's alphas = .86–.90), convergent validity, and discriminant validity (Watson et al., 1988).

3.2.6. Center for Epidemiologic Studies Depression Scale (CES-D)

The CES-D (Radloff, 1977) was used to determine baseline depression symptoms and incorporated as a covariate in all primary analyses. The CES-D is a self-report questionnaire designed to study depressive symptoms in the general population. The questionnaire includes 20 questions and focuses on the affective components of depression (Radloff, 1977). Participants rated how often they felt each symptom during the past week. There are 4 response options scored on a 4-point scale: 0 = rarely or none of the time (less than 1 day), 1 = some or a little of the time (1–2 days), 3 = occasionally or a moderate amount of time (3–4 days), 4 = all the time (5–7 days). The CES-D has demonstrated internal

consistency (Cronbach's alpha = .90), acceptable test-retest reliability, and excellent concurrent validity (Radloff, 1977).

3.3. Pattern Recognition Task (PRT)

A computer-administered pattern recognition task (PRT) designed to elicit a stress response (Azam et al., 2015) was used during the stress phase. The PRT consisted of 22 trials, and in each trial, 4 alphanumeric characters were presented for approximately 11 sec during which participants were expected to try to discern a pattern. Character sets were designed to plausibly resemble simple or complex patterns when in fact there were none. After approximately 11 sec, a 5th character was presented and participants were expected to quickly but accurately determine if it was pattern-consistent with the first 4 characters. Participants pressed the left arrow key for "True" if they believed the character was pattern-consistent and the right arrow key for "False" if they believed it was not. Immediately after responding, feedback with the text "Right Answer" or "Wrong Answer" was displayed on the screen along with a running total of "Correct" and "Incorrect" responses. The PRT was programmed to display "Right Answer" and "Wrong Answer" 50% of the time in a pre-defined and random sequence that was identical across participants. Before beginning the PRT, each participant was told that task performance reflected cognitive processing capacity and that the average score was approximately 80% with an average response time of 2 sec for each of the 22 trials.

3.4. Mindfulness Meditation Task

There were two treatment conditions: mindfulness meditation instruction (MMI) and mindfulness meditation description (MMD). MMI involved a 10 min recorded guided meditation emphasizing breath awareness and non-judgemental redirection of attention to breathing sensations upon noticing distracting thoughts or emotions. MMD, by contrast, involved a 10 min audio recording describing mindfulness concepts and related evidence without any instructional references.

3.5. Procedure

Testing was conducted in a University laboratory. Each participant was assessed in a single session. Participants were instructed to avoid food (for 2 hr), caffeine (for 3 hr), and vigorous exercise (for 24 hr) before their appointments. Upon arrival, participants provided written informed consent and completed electronically administered questionnaires.

The experiment adopted a repeated measures design consisting of three consecutive phases: resting baseline, stress exposure, and treatment. As the experiment was deemed useful for comparisons with another psychophysiological measure, pupil diameter, the experiment took place in a dimly lit room and incorporated use of a wearable eye tracker (Tobii Pro Glasses 2), a chin rest to optimize pupil measurement, and a fixation cross displayed on a computer screen to minimize eye movement. The present report omits the analytic details related to pupillometric data; analyses are planned for a future date.

The baseline phase required participants to sit for 5 min in a relaxed and upright position while resting their chin in a chinrest and their gaze on a fixation cross. Participants were instructed to think freely while remaining silent and avoiding sudden movements.

The stress phase employed the PRT. Immediately after the stress phase, participants were asked to complete the MIL-S and a manipulation check measuring perceived stress, performance, and task difficulty.

Participants were then randomly assigned to either the MMI condition or the MMD condition. Prior to the MMI/MMD recording, those assigned to MMI were provided brief meditation instructions that mirrored the MMI recording, and those assigned to MMD were instructed to try their best to relax. In both conditions, participants sat upright while resting their chin in a chinrest and their gaze on a fixation cross.

Immediately after the treatment phase, participants were asked to complete the MIL-S. Upon experiment completion, participants were debriefed and informed about the nature and purpose of deception (PRT).

3.6. Statistical Analyses

Prior to analyses, raw RMSSD and HF-HRV data were natural log transformed to adjust non-normality indicated by the Shapiro-Wilk test, *p*s < .001, and then rescaled by a multiple of 100; i.e., ln(RMSSD)*100 and ln(HF-HRV)*100.[2]

3.6.1. Hypothesis 1

Regression models were used to examine relationships between MLQ-P and 5-min VmHRV parameters at rest.

3.6.2. Hypothesis 2

Before testing hypotheses 2 (and 3) using longitudinal mixed models (LMM),[3] it was necessary to first model the expected minute-by-minute response trajectory of ln(RMSSD)*100 across phases using a linear spline (a piecewise function comprised of linear pieces joined at "knot" points [P. L. Smith, 1979]). Knots were placed at each phase transition (5.0 and 10.0 min) to allow for possible discontinuous change (slope and level change) and at the end of the first half of treatment (15.0 min) to

[2] Note that log differences of a variable reflect the approximate proportional change in that variable. Thus, in a regression where ln(RMSSD)*100 is, for example, the dependent variable, coefficients of linear predictors are directly interpretable as the approximate percentage change in RMSSD associated with a unit change in the linear predictor.

[3] While ANOVA models are commonly considered for longitudinal data, LMMs offer several key advantages. First, whereas ANOVA models assume categorical independent variables (IV), LMMs are not limited by this requirement, permitting interactions between continuous IVs (Hoffman & Rovine, 2007) – MLQ-P and time, for instance. Second, ANOVA models focus only on group changes, thus ignoring change at the individual level; LMMs, by contrast, retain this valuable information by incorporating individual growth parameters (i.e., intercepts and slopes; Hedeker & Gibbons, 2006; Shek & Ma, 2011). Third, repeated-measures ANOVAs impose a covariance structure that unrealistically assumes equal variances across all repeated measurements and equal correlations between any two repeated measurements. LMMs on the other hand, allow alternative covariance structures that more accurately reflect the varied covariance patterns of longitudinal data (Diggle et al., 2002, p. 114; Gueorguieva & Krystal, 2004; Hoffman & Rovine, 2007; Shek & Ma, 2011). Fourth, LMMs do not require balanced data across repeated measurements and can therefore accommodate subjects with missing data (Curran et al., 2010; Shek & Ma, 2011).

allow possible continuous change (slope change only). All spline parameters were allowed to vary randomly across individuals to capture differences in individual trajectories. Parameters were calculated using restricted maximum likelihood (REML) estimation. A second order autoregressive covariance structure [AR(2)] was fit to capture potential autocorrelation inherent in longitudinal data.

Assessing (a) stress-reactivity and (b) stress-attenuation as a function of MLQ-P involved testing the moderating effect of MLQ-P on ln(RMSSD)*100 trajectories from (a) min 5-0–6.0 (final baseline minute to stress onset) and from (b) min 6.0–10.0 (stress task progression).

3.6.3. Hypothesis 3

Examining the effect of MLQ-P and mindfulness on VmHRV recovery involved testing whether the interaction between MLQ-P and treatment condition (MMI vs. MMD) moderated ln(RMSSD)*100 trajectories during min 10.0–20.0 (treatment phase).

3.6.4. Hypothesis 4

LMMs with varying intercepts were used to test change in MIL-S across phases. To model the change from baseline (T_0) to post-stress (T_1) and from post-stress to post-treatment (T_2), a continuous linear spline with a knot at T_1 was used. Parameters were calculated using restricted maximum likelihood (REML) estimation.

3.6.5. Statistical Software and Tests

Wald tests were used for joint significance testing involving multiple regression parameters. Analyses were carried out using R version 4.0.0 with nlme (Pinheiro et al., 2020) to perform mixed-effects modeling and spida2 (Monette et al., 2019) for spline modeling and Wald testing. The significance threshold across analyses was defined as $p < .05$.

4. Results

Figure 1

Participant Flow Through Experimental Phases

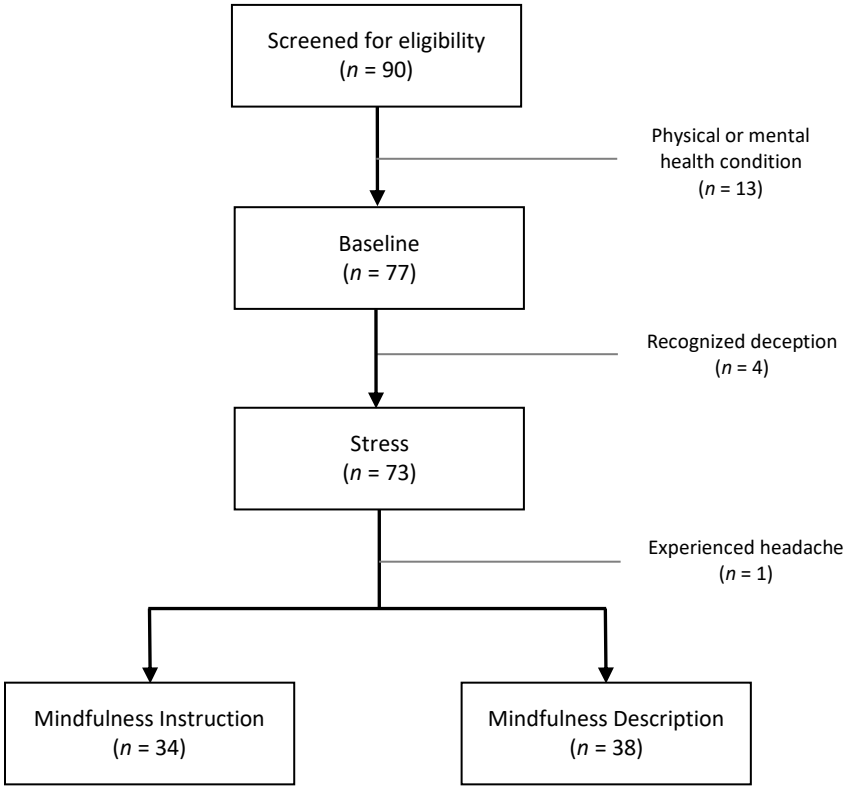


Figure 1 summarizes the flow of participants through experimental phases. Ninety participants (65 female; 25 male) were screened from October 2019 to February 2020. Thirteen participants were ineligible due to physical or mental health conditions (e.g., diabetes, cardiovascular disease, anxiety disorder), resulting in 77 healthy participants at baseline. Four participants recognized deception in the stress task and were excluded from post-baseline analyses. One participant experienced a headache during the treatment phase and was excluded from post-stress analyses. Four participants provided partial respiratory data due to respiratory belt malfunction. Sample characteristics are presented in Table 1.

Table 1

Demographic, Psychological, and Physiological Characteristics at Baseline (N = 77)

Variable	*n*(%) / *M*(*SD*)
Female	53 (68.8%)
Male	24 (31.2%)
Age	19.95 (2.29)
Education level	
High school	75 (97.4%)
College	1 (1.3%)
University	1 (1.3%)
Race/Ethnic origin	
African	7 (9.1%)
Caribbean	4 (5.2%)
Latin American	3 (3.9%)
West Asian	12 (15.6%)
South Asian	19 (24.7%)
Southeast Asian	8 (10.4%)
East Asian	3 (3.9%)
European/White	12 (15.6%)
Russian	1 (1.3%)
Multi-ethnic	8 (10.4%)
Psychological variables	
MLQ-P	23.18 (6.31)
MIL-S	13.00 (3.59)
PANAS-P	32.66 (6.71)
CES-D	18.35 (9.22)
VmHRV (5-min)	
Raw HF-HRV (ms^2)	1230.00 (1769.01)
Raw RMSSD (ms)	44.57 (25.26)
ln(HF-HRV)*100	647.84 (112.10)
ln(RMSSD)*100	366.74 (49.56)
Respiratory Frequency (5-min; bpm)	16.64 (3.93)

Note. Categorical variables reported as frequencies and percentages; numeric variables reported as *M*s and *SD*s. MLQ-P = Meaning in Life Questionnaire - Presence of meaning subscale; MIL-S = Meaning in Life – State Scale; PANAS-P = Positive and Negative Affect Schedule – Positive affect; CES-D = Center for Epidemiologic Studies Depression Scale; VmHRV = vagally-mediated heart rate variability; HF-HRV = high frequency heart rate variability; RMSSD = root mean square of successive differences between normal heartbeats.

4.1. Hypothesis 1: MLQ-P Is Positively Correlated With RMSSD and HF-HRV

A hierarchical multiple regression was conducted to examine the relationship between MLQ-P and RMSSD. MLQ-P was median-centered to improve interpretability of parameter estimates. RMSSD was derived from the full 5-min duration of the baseline phase. Results are summarized in Table 2.

Table 2

Hierarchical Regression Analysis Predicting RMSSD[a] From Meaning in Life, Positive Affect, Depressive Symptoms, and Respiration (N = 77)

Variable	*b*	*SE*	95% CI	*p*	R^2	ΔR^2
Model 1					.00	.00
MLQ-P (linear)	0.467	0.905	[-1.336, 2.271]	.607		
Model 2					.10	.09
MLQ-P	1.430	0.936	[-0.436, 3.295]	.131		
MLQ-P (quadratic)	0.300	0.109	[0.082, 0.518]	.008		
Model 3					.23	.13
MLQ-P	-0.054	1.032	[-2.112, 2.004]	.958		
MLQ-P (quadratic)	0.283	0.104	[0.075, 0.490]	.008		
PANAS-P	1.877	0.870	[0.143, 3.611]	.034		
CES-D	-0.654	0.654	[-1.959, 0.651]	.321		
Respiratory Frequency	-2.947	1.327	[-5.592, -0.301]	.030		

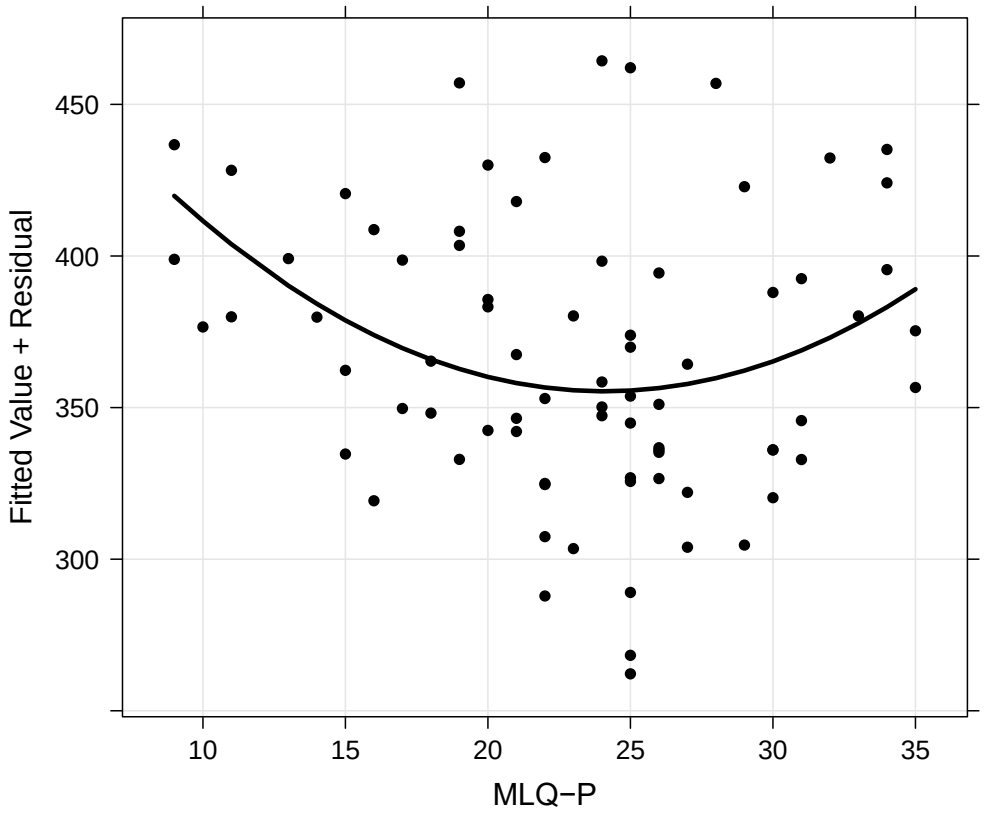
Note. *b* = unstandardized beta; RMSSD = root mean square of successive differences between normal heartbeats; MLQ-P = Meaning in Life Questionnaire - Presence of meaning subscale; PANAS-P = Positive and Negative Affect Schedule – Positive affect; CES-D = Center for Epidemiologic Studies Depression Scale.
[a]Natural log-transformed values rescaled by a multiple of 100.

As per model 1, there was no evidence of a linear relationship between MLQ-P and RMSSD, $F(1, 75) = 0.27$, $p = .607$; however, visual inspection of the data suggested a potential U-shaped relationship, which was supported by model 2, $R^2 = .10$, $\Delta R^2 = .09$, $F(2, 74) = 3.92$, $p = .024$. The quadratic relationship remained significant after controlling for positive affect, depressive symptoms, and respiration (model 3), $R^2 = .23$, $\Delta R^2 = .13$, $F(5, 71) = 4.24$, $p = .002$. This relationship is presented in Figure 2. An effect-size sensitivity analysis (G*Power 3.1) for an increase in R^2 from MLQ-P, given control variables, revealed a minimum detectable effect of $f^2_{\text{MLQ-P}|\text{Covariates}} = .13$ when $n = 77$, $\alpha = .05$, and $(1 - \beta) = .80$. The

corresponding observed effect size was $f^2_{\text{MLQ-P}|\text{Covariates}}$ = .12. MLQ-P was linearly related to positive affect, $r(77) = .44$, $p < .001$; and depressive symptoms $r(77) = -.48$, $p < .001$.

Figure 2

*Visualization of Relationship between ln(RMSSD)*100 and Meaning in Life, Adjusted for Positive Affect, Depressive Symptoms, and Respiration (N = 77)*



Note. Component-plus-residual plot for MLQ-P in the regression of ln(RMSSD)*100 on MLQ-P, adjusting for covariates CES-D, PANAS-P, and respiratory frequency. Fitted values are predicted values of ln(RMSSD)*100 when covariates are held constant at their mean value; residuals are from the regression. (For a review of component-plus-residual plots, see Cook, 1993; Wood, 1973.) RMSSD = root mean square of successive differences between normal heartbeats; MLQ-P = Meaning in Life Questionnaire - Presence of meaning subscale; PANAS-P = Positive and Negative Affect Schedule – Positive affect; CES-D = Center for Epidemiologic Studies Depression Scale.

Results were similar when 5-min HF-HRV was regressed on the same variables. Table 3 presents the full model, $R^2 = .295$, $F(5, 71) = 5.95$, $p < .001$. The observed effect size of MLQ-P given control variables was $f^2_{\text{MLQ-P}|\text{Covariates}} = .08$.

Table 3

Multiple Regression Analysis Predicting HF-HRV[a] From Meaning in Life, Positive Affect, Depressive Symptoms, and Respiration (N = 77)

Variable	*b*	*SE*	95% CI	*p*
MLQ-P	0.864	2.234	[-3.589, 5.318]	.700
MLQ-P (quadratic)	0.537	0.225	[0.088, 0.986]	.020
PANAS-P	3.164	1.882	[-0.589, 6.917]	.097
CES-D	-1.058	1.416	[-3.881, 1.766]	.458
Respiratory Frequency	-11.471	2.871	[-17.195, -5.746]	< .001

Note. *b* = unstandardized beta; HF-HRV = high-frequency heart rate variability; MLQ-P = Meaning in Life Questionnaire - Presence of meaning subscale; PANAS-P = Positive and Negative Affect Schedule – Positive affect; CES-D = Center for Epidemiologic Studies Depression Scale.
[a]Natural log-transformed values rescaled by a multiple of 100.

The regression analysis therefore suggests that VmHRV parameters (RMSSD and HF-HRV) were relatively low at moderate levels of MLQ-P but tended to increase as MLQ-P increased *or* decreased even after controlling for important confounders.

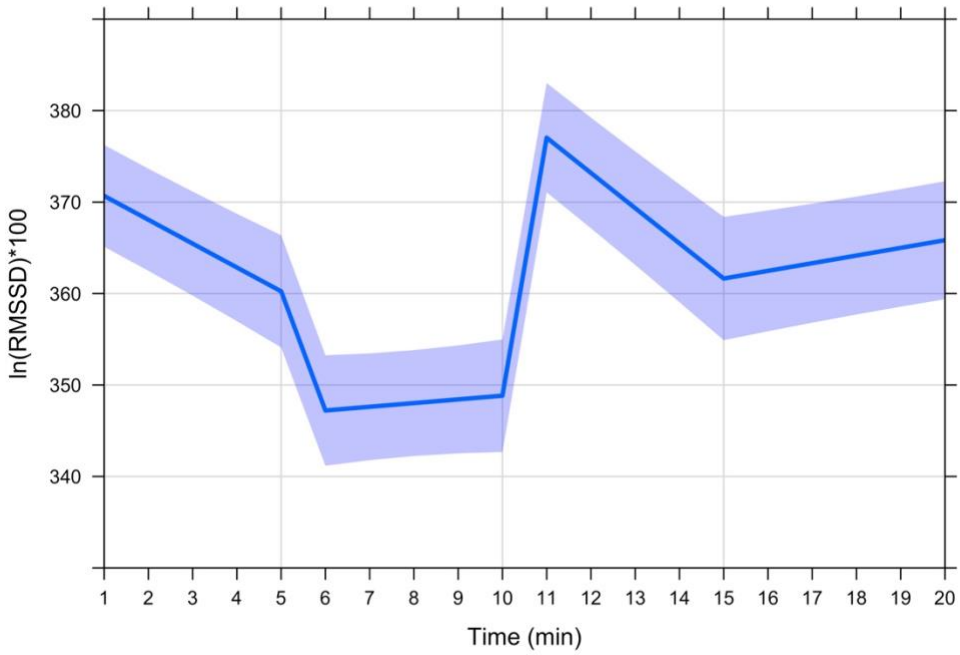
4.2. Hypothesis 2: MLQ-P Is Differentially Associated With Stress Responding as Measured by RMSSD.

4.2.1. Preliminary Step 1: Modelling the Expected RMSSD Trajectory Across 20 Min

To examine potential interactions between MIL and stress-responding across protocol phases, it was necessary to first model the expected response trajectory across the entire 20 min protocol (base model without moderating variables; e.g., MLQ-P). The expected trajectory is plotted in Figure 3 and its corresponding parameter coefficients, parameter variability, and significance levels are presented in Table 4.

Figure 3

Expected RMSSD Trajectory Across 20 Minutes



Note. The plot depicts the expected minute-by-minute ln(RMSSD)*100 trajectory across the three experimental phases spanning 20 minutes. RMSSD = root mean square of successive differences between normal heartbeats. Error bands represent ±1 standard error.

Table 4

Results From Longitudinal Modeling of Estimated RMSSD[a] Trajectory Change Parameters Across Experimental Phases

Experimental phase	Estimate	*SE*	95% CI	*t*(1387)	*p*
Baseline (0.0–5.0 min)					
Intercept (0.0–1.0 min)	370.68	5.56	[359.76, 381.59]	66.62	< .001
Slope (1.0–5.0 min)	-2.61	0.70	[-3.99, -1.23]	-3.71	< .001
Stress (5.0–10.0 min)					
Jump (baseline to stress; 5.0–6.0 min)	-13.43	5.67	[-24.56, -2.30]	-2.37	.018
Relative slope change (stress vs. baseline)	3.01	1.14	[0.78, 5.25]	2.64	.008
Slope (6.0–10.0 min)	0.40	0.96	[-1.47, 2.28]	0.42	.673
Treatment (1st half; 10.0–15.0 min)					
Jump (stress to treatment; 10.0–11.0 min)	32.06	4.32	[23.58, 40.54]	7.42	< .001
Relative slope change (treatment 1st half vs. stress)	-4.25	1.08	[-6.38, -2.13]	-3.93	< .001
Slope (11.0–15.0 min)	-3.85	0.72	[-5.26, -2.44]	-5.35	< .001
Treatment (2nd half; 15.0–20.0 min)					
Relative slope change (treatment 2nd vs 1st half)	4.69	1.10	[2.53, 6.85]	4.25	< .001
Slope (15.0–20.0 min)	0.84	0.52	[-0.18, 1.86]	1.61	.107

Note. RMSSD = root mean square of successive differences between normal heartbeats.
[a]Natural log-transformed values rescaled by a multiple of 100.

The intercept parameter denotes the mean RMSSD during the first baseline minute. Three types of change parameters related to RMSSD are described: (1) slope parameters describe the intra-phase rate of change, (2) “Jump” parameters describe abrupt level change related to phase transition (e.g., from baseline to stress onset), and (3) relative slope change parameters describe the change in slope compared to the slope in the period just before. Altogether, the expected response trajectory is characterized by

- a gradual RMSSD decrease during baseline,
- a marked RMSSD decrease at stress onset,
- positive slope change from baseline to stress, but no evidence of a significant slope during stress,

- a marked RMSSD increase at treatment onset,
- a gradual RMSSD decrease during the first half of treatment, and
- positive slope change from the first half of treatment to the second half, but no evidence of a significant slope during the second half of treatment.

4.2.2. Preliminary Step 2: Incorporating MLQ-P as a Moderator, Holding Mood Variables Constant

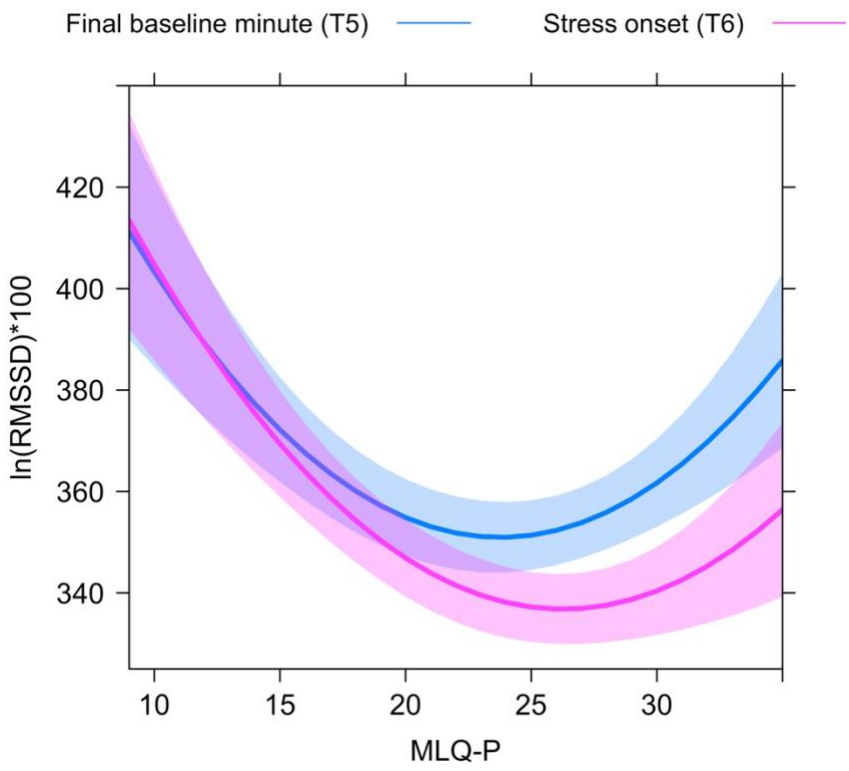
MLQ-P was then included in the base model as a moderating variable to assess its potential relationship with the expected trajectory – that is, whether trajectories varied as a function of MLQ-P. Given evidence of a quadratic relationship between MLQ-P and VmHRV, the quadratic polynomial of MLQ-P was used in the model. PANAS-P and CES-D were included as covariates.

4.2.3. Hypothesis 2a: Higher MLQ-P Is Associated With Less Stress-Reactivity (Smaller RMSSD Reductions) at Stress Onset.

A Wald test was used to assess whether MLQ-P moderated the effect of stress on RMSSD with mood variables held constant. There was evidence of a significant interaction between MLQ-P and stress onset (from min 5.0–6.0), $F(2, 1383) = 5.35$, $p = .005$. Stated differently, there was evidence of variability in RMSSD level change at stress onset as a function of MLQ-P. Figure 4 illustrates the response variability expected from the final baseline minute (T_5) to the first stress minute (T_6) and Figure 5 plots the difference between the two response curves ($T_6 - T_5$). Table 5 provides corresponding difference estimates for low, medium, and high values (10^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} percentiles) of MLQ-P.

Figure 4

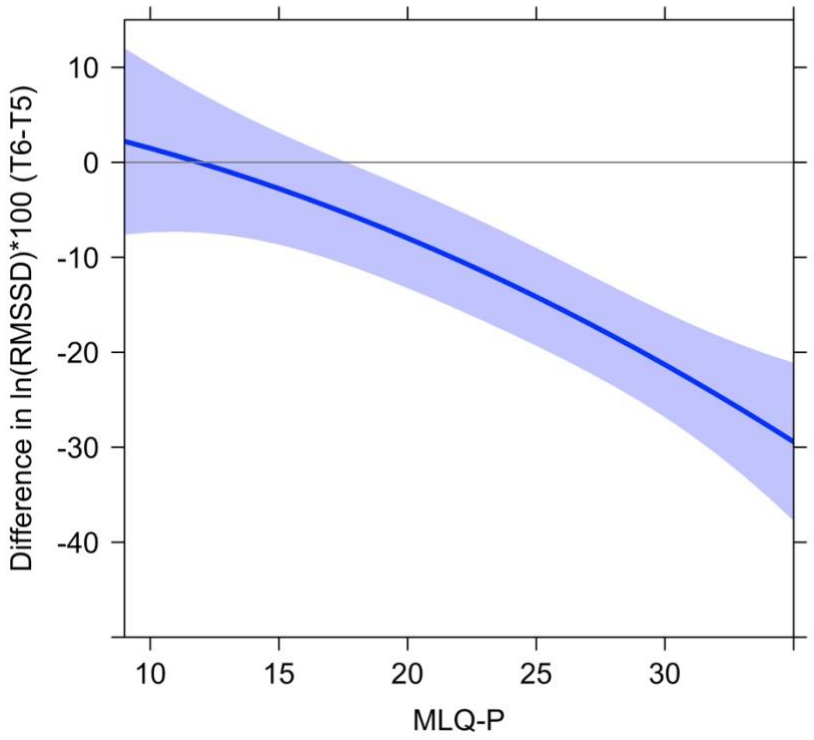
Expected RMSSD Changes From Final Baseline Minute to First Stress Minute as a Function of Meaning in Life (MLQ-P)



Note. The plot shows the expected ln(RMSSD)*100 at T_5 (final baseline minute) and T_6 (first stress minute) as a function of MLQ-P, controlling for positive affect and depressive symptoms. RMMSD = root mean square of successive differences between normal heartbeats. Error bands represent ±1 standard error.

Figure 5

Expected RMSSD Differences Between the Final Baseline Minute and First Stress Minute as a Function of Meaning in Life (MLQ-P)



Note. The plot shows the predicted change in ln(RMSSD)*100 from the final baseline minute (T_5) to the first stress minute (T_6) as a function of MLQ-P, controlling for positive affect and depressive symptoms. RMSSD = root mean square of successive differences between normal heartbeats. Error bands represent ±1 standard error.

Table 5

Expected RMSSD[a] Differences Between Final Baseline Minute to First Stress Minute at Different Levels of Meaning in Life

Parameter	Estimate	*SE*	95% CI	*t*(1383)	*p*
Level change					
10th percentile (MLQ-P = 15)	-2.79	6.56	[-15.66, 10.07]	-0.43	.670
25th percentile (MLQ-P = 19)	-7.18	5.96	[-18.87, 4.52]	-1.20	.229
50th percentile (MLQ-P = 24)	-13.37	5.84	[-24.83, -1.92]	-2.29	.022
75th percentile (MLQ-P = 27)	-17.47	5.82	[-28.88, -6.06]	-3.00	.003
90th percentile (MLQ-P = 31)	-23.38	6.50	[-36.14, -10.62]	-3.60	< .001

Note. Results incorporate mood covariates (positive affect from the Positive and Negative Affect Schedule and depressive symptoms from the Center for Epidemiologic Studies Depression Scale). RMMSD = root mean square of successive differences between normal heartbeats; MLQ-P = Meaning in Life Questionnaire - Presence of meaning subscale.
[a]Natural log-transformed values rescaled by a multiple of 100.

Per Table 5, high MLQ-P levels were associated with greater level changes in RMSSD compared to moderate MLQ-P levels. By contrast, there was no evidence of level change in RMSSD at low MLQ-P levels.

The evidence therefore suggests that at stress onset, higher MLQ-P was associated with larger reductions in RMSSD.

This interaction remained significant after adjusting for respiration, $F(2, 1370) = 4.07$, $p = .017$, but in contrast to the results presented in Table 5, only the level change at the 90th percentile of MLQ-P was significant (estimate = -12.39, $SE = 5.87$, 95% CI [-23.91, 0.883]), $t(1370) = -2.11$, $p = .035$.

4.2.4. Hypothesis 2b: Higher MLQ-P Predicts Faster Stress Attenuation (More Positive RMSSD Trajectories) During Stress

There was no evidence of variability in slope change (baseline vs. stress) as a function of MLQ-P, $F(2, 1383) = 0.60$, $p = .551$. Stated differently, different levels of MLQ-P were not differentially associated with parasympathetic control for the remainder of the stress task. Instead, slopes appeared parallel and

sustained across MIL levels as evidenced by slopes indistinguishable from zero with small *SE*s (see Appendix A).

This interaction remained non-significant after adjusting for respiration, $F(2, 1370) = 0.61$, $p = .941$.

4.3. Hypothesis 3: MMI (Active Treatment) Facilitates Faster Recovery (More Positive RMSSD Trajectories) as a Function of Higher MLQ-P Compared to MMD (Control Treatment)

4.3.1. Step 1: Testing the Moderating Effect of Treatment Condition (MMI vs. MMD)

To assess MMI's effect on response trajectories (relative to MMD's effect), differences in level and slope changes were analyzed. There was no evidence of significant differences related to treatment $F(3, 1384) = 0.64$, $p = .591$. MMI therefore appeared neither more nor less effective in facilitating post-stress parasympathetic recovery compared to MMD.

Results remained non-significant after entering respiration as a covariate, but *p*-values were substantially changed $F(3, 1371) = 1.84$, $p = .139$; a detailed comparison is provided in Table 6.

Table 6

Comparison of RMSSD[a] Change During Treatment Phase (MMI vs. MMD) Before and After Adjusting for Respiration

Parameter (additional change related to MMI)	Estimate	*SE*	95% CI	*t*[b]	*p*
Without respiration					
Level change (stress to treatment; 10-11 min)	0.25	5.66	[-10.84, 11.35]	0.04	.964
Relative slope change (treatment 1st half vs. stress)	-1.32	1.43	[-4.12, 1.48]	-0.93	.354
Relative slope change (treatment 2nd vs 1st half)	1.25	2.15	[-2.96, 5.46]	0.58	.561
With respiration					
Level change (stress to treatment; 10-11 min)	0.86	5.36	[-9.65, 11.37]	0.16	.872
Relative slope change (treatment 1st half vs. stress)	-2.42	1.30	[-4.97, 0.13]	-1.86	.062
Relative slope change (treatment 2nd vs 1st half)	2.74	1.99	[-1.17, 6.64]	1.37	.170

Note. Results incorporate mood covariates (positive affect from the Positive and Negative Affect Schedule and depressive symptoms from the Center for Epidemiologic Studies Depression Scale). RMSSD = root mean square of successive differences between normal heartbeats; MMI = Mindfulness Meditation Instruction. MMD = Mindfulness Meditation Description. Reference category = MMD.
[a]Natural log-transformed values rescaled by a multiple of 100.
[b]*df* without respiration = 1384; *df* with respiration = 1371.

4.3.2. Step 2: Testing the Moderating Effect of MLQ-P x Treatment Condition

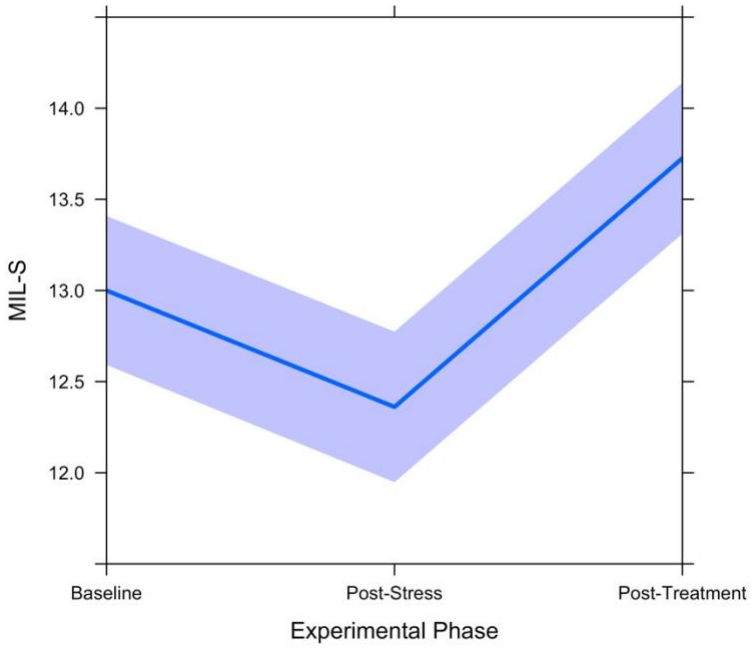
The next step involved testing whether an interaction between MLQ-P and treatment condition (MMI vs. MMD) moderated treatment response trajectories while controlling for mood variables (PANAS-P and CES-D). There was no evidence that trajectories varied as a function of MLQ-P and treatment condition, $F(6, 1372) = 0.57$, $p = .755$. Therefore, there was no evidence that MMI was more or less effective in facilitating post-stress parasympathetic recovery at higher levels of MLQ-P compared to MMD. Results remained non-significant after entering respiration as a covariate, $F(6, 1359) = 0.49$, $p = .817$.

4.4. Hypothesis 4: State MIL (MIL-S) Is Affected By Exposure.

A longitudinal mixed model with varying intercepts was used to examine MIL state changes across experiment phases. A spline with a knot at the end of the stress phase was used to allow continuous change at the transition from stress to treatment exposure. The expected trajectory is plotted in Figure 6 and its corresponding parameter coefficients, parameter variability, and significance levels are presented in Table 7.

Figure 6

Expected MIL-S Trajectory Across Experimental Phases



Note. The plot depicts the main effect of change in MIL-S ratings measured at baseline, immediately after stress, and immediately after treatment. MIL-S = meaning in life – state scale. Error bands represent ±1 standard error.

Table 7

Changes in State Meaning in Life (MIL-S) Across Experimental Phases

Parameter	Estimate	*SE*	*t*(143)	*p*
Baseline (T_0)	13.00	0.41	31.82	< .001
Change from baseline (T_0) to post-stress (T_1)	-0.64	0.28	-2.27	.025
Change from post-stress (T_1) to post-treatment (T_2)	2.00	0.49	4.10	< .001

Note. MIL-S ratings were measured at baseline, immediately after stress, and immediately after treatment.

4.4.1. Hypothesis 4a: Stress Is Associated With Lower MIL-S

As per Table 7, negative change in MIL-S from baseline to post-stress was significant (estimate = -0.64, *SE* = 0.28), *t*(143) = -2.27, *p* = .025.

4.4.2. Hypothesis 4b: Mindfulness Meditation Is Associated With Faster Change in MIL-S

Examining the effect of MM involved testing the difference between MMI and MMD in stress-to-treatment slope change – that is, whether MM condition moderated MIL-S change from the end of stress to the end of treatment. There was no evidence of a difference (estimate = 0.05, *SE* = 0.98), $t(141) = 0.05$, $p = .958$, suggesting that MM instruction was neither more nor less effective in raising state MIL compared to MM description.

4.4.3. Hypothesis 4b (Exploratory): Treatment Exposure (Regardless of Condition) Is Associated With MIL-S Change

Without evidence that MMI and MMD were differentially effective in raising MIL-S, the variable of treatment condition was removed from the model to examine the main effect of treatment exposure on MIL-S. As per Table 7, the change from post-stress to post-treatment was significant (estimate = 2.00, *SE* = 0.49), $t(143) = 4.10$, $p < .001$.

4.4.4. Hypothesis 4c: State MIL Will Increase From Baseline to Post-Treatment

In keeping with results from Hypothesis 4b, MM condition as a categorical variable was not included in the testing of Hypothesis 4c. The increase in expected values from baseline to post-treatment was significant (estimate = 0.73, *SE* = 0.28), $t(143) = 2.57$, $p = .011$.

Altogether, results suggest that state MIL is amenable to change after stress exposure and treatment exposure. While MM instruction appeared neither more nor less effective than MM description, both appeared effective in improving state MIL to levels exceeding baseline.

5. Discussion

5.1. Non-Linear Association Between MIL and Cardiac Vagal Tone

This study examined associations between MIL and VmHRV under resting, stress-induced, and intervention conditions. Regression analyses revealed a quadratic, non-monotonic relationship between MIL and VmHRV parameters (RMSSD and HF-HRV) at baseline, suggesting that high *and* low MIL levels were associated with greater parasympathetic nervous system (PNS) activation than moderate MIL levels.

Higher VmHRV typically predicts healthy states, while lower VmHRV is usually predictive of physical and mental disorder. However, these findings have not included non-linear associations (Duarte & Pinto-Gouveia, 2017; Kogan et al., 2014) that contrast with the linear assumptions of the Neurovisceral Integration Model. In these non-linear exceptions, higher VmHRV predicts depression (Kogan et al., 2013), and depressive symptoms (e.g., sadness) correlate with higher VmHRV (Kreibig, 2010; Rochman & Diamond, 2008; Rottenberg, 2007). Theoretically, the higher baseline PNS (VmHRV) levels associated with lower MIL could reflect chronic disengagement (Maddi, 1967) linked to boredom, apathy, and life devaluation (Frankl, 1963; Klinger, 2012). Indeed, boredom is an empirically-supported feature of meaninglessness (Fahlman et al., 2009), and boredom experiences also correspond with VmHRV increases during monotonous tasking[4] (Pattyn et al., 2008).

Reflecting the non-linear relationship, movement towards moderate MIL was associated with lower VmHRV (greater PNS withdrawal), an observation reflecting meaning-as-engagement perspectives, where life engagement replaces meaninglessness, but at the cost of added stress and anxiety (Frankl, 1963; Yalom & Josselson, 2019). In existential writings, individuals with meaningful goals

[4] Interestingly, monotonous tasks designed to induce boredom also predict patterns of higher VmHRV (Keller et al., 2011; Tozman et al., 2015).

also confront anxiety in being responsible for their own life-design (Yalom, 1980) and stress in advancing valued goals (Bronk, 2014; Lazarus & DeLongis, 1983), all of which plausibly lead to lower basal VmHRV.

The final quadratic component links high MIL with higher VmHRV. Although this finding seemingly contradicts discussions on the stress of meaningful living, such stress is conceivably counteracted by the positive relationships between high MIL and self-regulation. In particular, being on a meaningful life path can lead to inner calm and composure (Lukas, 1992), and a vigorous self-developmental process associated with hardiness (Maddi, 2004, 2012). Each meaningful action can increase the self-efficacy with which the stresses of purposeful activity are effectively managed (Maddi et al., 2011). As adaptive self-regulatory processes correspond with higher VmHRV (Denson et al., 2011; Volokhov & Demaree, 2010), the calmer, more parasympathetically dominant states associated with high MIL conceivably reflect the long-term effects of positive self-regulation.

Altogether, the quadratic MIL-VmHRV relationship describes a relationship consistent with theoretical and empirical perspectives where low MIL levels are associated with disengaged, low mobilization states (higher VmHRV and PNS activity), while moderate MIL levels involve greater life engagement and higher stress (lower VmHRV), and high MIL levels are related to healthy adaptation that lowers stress susceptibility (higher VmHRV). Given divergent findings in the wellbeing-VmHRV literature (for a review of linear, quadratic, and null effects, see Balzarotti et al., 2017), the present finding highlights the need to rigorously test and integrate non-linear hypotheses in future studies.

5.2. MIL and Cardiac Vagal Reactivity

Given arguments linking meaning to enhanced coping, Hypothesis 2a followed the assumption that higher MIL would predict less stress-reactivity (i.e., smaller VmHRV decreases, or less cardiac vagal reactivity [CVR] resulting from stress). Instead, results show that those with higher MIL demonstrated larger VmHRV decreases (i.e., larger effect sizes) at stress onset compared to other MIL levels.

This finding contrasts findings from Ishida & Okada (2006), which indicated greater CVR in individuals with lower purpose in life. This divergence may be due to differences in stress tasks. Whereas the present study employed a cognitively demanding stressor, Ishida & Okada's (2006) stressor involved a rollercoaster video that was designed to elicit fear, but was arguably more passive in nature. Along these lines, past CVR findings have been mixed, with investigators attributing inconsistencies to heterogeneity in the types of stressors used (e.g., passive viewing tasks vs. stressors involving effortful processes; Balzarotti et al., 2017; Bosch et al., 2001). The present study was also discrepant in that it assessed minute-by-minute stress reactivity, providing much finer temporal resolution than the 5 min averages used by Ishida & Okada (2006). It is possible that their analysis failed to capture important between-subject variability *within* the stress period. Nonetheless, the present finding is consistent with other work (Schaefer et al., 2013) demonstrating life purpose as a positive predictor of stress reactivity (measured via eyeblink startle reflex), which is largely convergent with emerging themes in the CVR literature.

Although less CVR (smaller VmHRV decreases) during stress exposure may reflect self-regulatory success in certain contexts (Gouin et al., 2014; G. Park et al., 2014; Thayer et al., 2012), from the polyvagal perspective, greater CVR in response to demanding activity serves adaptive outcomes like improved attention, information processing (Porges, 2011), and task engagement (Akinola & Mendes, 2014; Duschek et al., 2009; Mukherjee et al., 2011; Taelman et al., 2011). As life meaning emerges from engagement, a greater physiological propensity to mobilize and respond to situations via greater CVR may be an important component of how meaning develops in individuals exhibiting high MIL.

A growing literature also links greater CVR to better social functioning outcomes such as less loneliness (Muhtadie et al., 2015, Study 2), greater interpersonal warmth (Diamond & Cribbet, 2013), and pro-sociality (Obradović et al., 2010). Researchers reason that CVR may serve as a physiological indicator of social sensitivity linked to better detections of social cues (Human and Mendes, 2018;

Muhtadie et al., 2015, Study 3). Given the prevailing view that social relationships imbue life with meaning, associations between CVR and social functioning provide a coherent account of why higher MIL was associated with greater CVR as opposed to less.

Furthermore, consistent with research relating high MIL to enhanced self-regulation, high CVR in the context of high resting VmHRV has been linked to fewer internalizing symptoms (Hinnant & El-Sheikh, 2009) and less use of maladaptive mood repair strategies (e.g., rumination and avoidance) associated with depression (Yaroslavsky et al., 2013).

Altogether, the observed association between high MIL and greater CVR converges with prominent themes (engagement, social aptitude, and self-regulation) identified in both MIL and CVR literatures.

The hypothesized relationship between higher MIL and quicker stress attenuation under continued stressor exposure was not supported. Instead, stress effects appeared sustained and parallel (effect sizes similarly close to zero) across MIL levels throughout the stress task. These results suggest that MIL did not buffer the effect of ongoing stress, although further studies are needed to confirm this finding across a range of stressor exposures.

5.3. MIL, Mindfulness Meditation, and Cardiac Vagal Recovery

Finally, mindfulness meditation (MM; active vs. control) did not appear to interact with MIL in moderating the rate of post-stress VmHRV recovery. Despite adequate power, active MM also did not moderate recovery trajectories prior to adding MIL as an interaction term. Perhaps 10 min of mindfulness was too brief an epoch for significant between-group differences to emerge. It is also plausible that the control condition was too similar to the active condition to control for expectancy effects. A third possibility is that the control condition (passive listening) was itself calming as evidenced by the main effect of positive slope change during the second half of treatment.

5.4. Mindfulness Meditation and States of Life Meaning

The prediction that MM enhances MIL (after stress and relative to baseline) was partially supported; i.e., when both active and control MM conditions were combined. Mirroring the previous discussion, it is possible that both conditions were too alike to demonstrate differential effectiveness. Alternatively, it is possible that mood, a known MIL antecedent, was the primary source of MIL change and that MM, regardless of condition, had little actual influence. More specifically, completing the stressful task may have produced a "rebound effect" (Solomon, 1980) where relief from distress is followed by improved affect (Bolger et al., 1989; DeLongis et al., 1988; K. J. Williams et al., 1991) and in this case, enhanced meaning. Without a "pure" control condition or time-varying mood assessments, such questions are open to future inquiry.

Another explanation for the undifferentiated effects is that a mere 10 min of active MM may have been insufficient to access the hypothesized mechanisms of mindfulness-to-meaning theory (e.g., reappraisal, attentional broadening, and meta-awareness). In fact, many traditions emphasize the importance of preliminary practice prior to formal MM practice (D. Brown, 2009; D. P. Brown & Engler, 1980; Compton & Becker, 1983; Trungpa, 2013). Indeed, dose-response patterns have been observed where during meditation, more experienced meditators (who presumably need less time to enter meditative states) exhibit greater gamma wave activity (linked to heightened awareness and large scale neuronal integration; Lee et al., 2018; Lutz et al., 2004), and improved neural connectivity between brain networks potentially involved in meaning-making processes (Froeliger et al., 2012).

Nonetheless, these results provide evidence that MIL is modifiable within brief intervals and that each moment may be a potential source of meaning. This finding complements previous work showing stability and instability in day-to-day meaning as a dimension of MIL (Steger & Kashdan, 2013), and other research demonstrating positive covariation between daily meaningful activity and daily meaning salience, a state-like variant of MIL (Hooker et al., 2020).

Given the rise of therapeutic modals emphasizing present-moment timeframes (Hayes et al., 2004), reconstruing MIL as a state experience with moment-to-moment fluidity has obvious clinical implications.

5.5. Limitations and Future Directions

This study had several limitations. First, our sample was drawn from a student population and may not generalize to other populations. Maturation, for instance, may amplify the importance of meaning (Krause, 2012), and searching for it at later life stages may be associated with greater distress (Steger et al., 2009). It may be informative for future studies to explore whether patterns between VmHRV and MIL differ at different life stages.

Second, the MLQ-P aggregates aspects of MIL (coherence, purpose, and mattering) into a single omnibus score. As such, whether such aspects are differentially associated with VmHRV is unknown. Further identification of such associations would help refine conceptual definitions of MIL and reveal clearer intervention targets. Such detail may also delineate various meaning and meaninglessness sub-types. Incoherence resulting from a moral injury, for example, may carry a different physiological signature than incoherence resulting from grief. Future efforts to discern MIL-VmHRV associations should consider the use of newer multi-dimensional MIL measures (for recent measures, see Costin & Vignoles, 2020; George & Park, 2017).

Third, because of the cross-sectional nature of the curvilinear MIL-VmHRV relationship, interpretations should be made with caution. Sustained MIL deficits could conceivably lead to longitudinal reductions in VmHRV, given that less MIL is associated with less health-oriented behavior (Hooker & Masters, 2016, 2018; E. S. Kim et al., 2014), which correlates with lower VmHRV (Prinsloo et al., 2014; Sandercock et al., 2005). Moreover, because the effect size of the curvilinear model was smaller than the minimum detectable effect size expected with our study's sample size, further studies are needed to confirm this finding.

Fourth, RMSSD and HF-HRV largely represent the parasympathetic branch of the ANS, limiting the interpretability of the present findings. Future research would optimally focus on also incorporating sympathetically-mediated parameters such as pre-ejection period.

Finally, physical impositions necessitated by pupillometric assessment (fixed eye gaze and chin rest use) may have introduced extraneous behavioral elements, especially during the MM phase. Having to meditate with eyes open for example, may have hindered mindfulness processes (e.g., attentional focusing). Future research should replicate our study without such physical constraints.

5.6. Conclusion

MIL is widely viewed as a central motivating force with health implications traced to physiological processes. The present study provides preliminary evidence that MIL is quadratically linked to cardiac vagal tone, positively linked to cardiac vagal reactivity, and readily modifiable. These findings contribute to the ongoing search for physiological mechanisms linking meaning to health and the enduring project of maximizing meaningful living. By offering a novel view of MIL physiology and MIL plasticity, this research may be a positive step for therapeutic developments in clinical and health psychology.

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Appendices

Appendix A

Estimated RMSSD[a] Rate of Change During Stress Phase (6.0–10.0 Min) at Different Levels of Presence of Meaning in Life

Parameter	Estimate	*SE*	95% CI	*t*(1383)	*p*
Slope					
10th percentile (MLQ-P = 15)	0.03	1.02	[-1.98, 2.03]	0.02	.980
25th percentile (MLQ-P = 19)	0.32	0.98	[-1.61, 2.25]	0.32	.748
50th percentile (MLQ-P = 24)	0.52	0.98	[-1.39, 2.44]	0.54	.591
75th percentile (MLQ-P = 27)	0.57	0.97	[-1.35, 2.48]	0.58	.562
90th percentile (MLQ-P = 31)	0.52	1.02	[-1.48, 2.52]	0.51	.608

Note. Results incorporate mood covariates (positive affect from the Positive and Negative Affect Schedule and depressive symptoms from the Center for Epidemiologic Studies Depression Scale). RMSSD = root mean square of successive differences between normal heartbeats; MLQ-P = Meaning in Life Questionnaire - Presence of meaning subscale.

[a]Natural log-transformed values rescaled by a multiple of 100.

Appendix B: Meaning in Life Questionnaire (MLQ)

Meaning in Life Questionnaire

Please take a moment to think about what makes your life and existence feel important and significant to you. Please respond to the following statements as truthfully and accurately as you can, and also please remember that these are very subjective questions and that there are no right or wrong answers. Please answer according to the scale below:

* MLQ

	Absolutely Untrue 1	Mostly Untrue 2	Somewhat Untrue 3	Can't Say True or False 4	Somewhat True 5	Mostly True 6	Absolutely True 7
I understand my life's meaning.	○	○	○	○	○	○	○
I am looking for something that makes my life feel meaningful.	○	○	○	○	○	○	○
I am always looking to find my life's purpose.	○	○	○	○	○	○	○
My life has a clear sense of purpose.	○	○	○	○	○	○	○
I have a good sense of what makes my life meaningful.	○	○	○	○	○	○	○
I have discovered a satisfying life purpose.	○	○	○	○	○	○	○
I am always searching for something that makes my life feel significant.	○	○	○	○	○	○	○
I am seeking a purpose or a mission for my life.	○	○	○	○	○	○	○
My life has no clear purpose.	○	○	○	○	○	○	○
I am searching for meaning in my life.	○	○	○	○	○	○	○

Appendix C: Meaning in Life – State Scale (MIL-S)

Meaning in Life State Scale

Please respond to the following statements as truthfully and accurately as you can, and also please remember that these are very subjective questions and that there are no right or wrong answers. Please answer according to the scale below

* MILS

	Not at all	A little	A good deal	Very much so
Right now, I feel I have a meaningful life	○	○	○	○
Right now, I feel I have a satisfying purpose	○	○	○	○
Right now, my activities feel consistent with my life goals and purpose in life	○	○	○	○
Right now, life makes sense	○	○	○	○
Right now, my life feels worthwhile	○	○	○	○

Appendix D: The Positive and Negative Affect Schedule (PANAS)

The Positive and Negative Affect Schedule

This scale consists of a number of words that describe different feelings and emotions. Read each item and then mark the appropriate answer in the space next to that word. Indicate to what extent you have felt this way during the past week.

* PANAS

	very slightly or not at all	a little	moderately	quite a bit	extremely
interested	○	○	○	○	○
distressed	○	○	○	○	○
excited	○	○	○	○	○
upset	○	○	○	○	○
strong	○	○	○	○	○
guilty	○	○	○	○	○
scared	○	○	○	○	○
hostile	○	○	○	○	○
enthusiastic	○	○	○	○	○
proud	○	○	○	○	○
irritable	○	○	○	○	○
alert	○	○	○	○	○
ashamed	○	○	○	○	○
inspired	○	○	○	○	○
nervous	○	○	○	○	○
determined	○	○	○	○	○
attentive	○	○	○	○	○
jittery	○	○	○	○	○
active	○	○	○	○	○
afraid	○	○	○	○	○

Appendix E: Center for Epidemiological Studies-Depression (CES-D)

Center for Epidemiologic Studies Depression Scale

Below is a list of the ways you might have felt or behaved. Please indicate how often you have felt this way during the past week.

* CES-D

	Rarely or none of the time (less than 1 day)	Some or a little of the time (1-2 days)	Occasionally or a moderate amount of time (3-4 days)	Most or all of the time (5-7 days)
1. I was bothered by things that usually don't bother me	○	○	○	○
2. I did not feel like eating; my appetite was poor	○	○	○	○
3. I felt that I could not shake off the blues even with help from my family or friends	○	○	○	○
4. I felt that I was just as good as other people	○	○	○	○
5. I had trouble keeping my mind on what I was doing	○	○	○	○
6. I felt depressed	○	○	○	○
7. I felt that everything I did was an effort	○	○	○	○
8. I felt hopeful about the future	○	○	○	○
9. I thought my life had been a failure	○	○	○	○
10. I felt fearful	○	○	○	○
11. My sleep was restless	○	○	○	○
12. I was happy	○	○	○	○
13. I talked less than usual	○	○	○	○
14. I felt lonely	○	○	○	○
15. People were unfriendly	○	○	○	○
16. I enjoyed life	○	○	○	○
17. I had crying spells	○	○	○	○
18. I felt sad	○	○	○	○
19. I felt that people disliked me	○	○	○	○
20. I could not "get going"	○	○	○	○

Appendix F: Study Consent Form

Study Consent Form

Study Name: MEASURING RELATIONS BETWEEN MEANING IN LIFE, STRESS, AND MINDFULNESS MEDITATION USING HEART RATE VARIABILITY AND PUPILLOMETRY

Principal Investigator
Kevin Dang
School of Kinesiology and Health Science
E-mail: kvndang@my.yorku.ca
Office: 138 Chemistry Building, York University

You are being asked to take part in a research study. Before agreeing to take part in this study, it is important that you read and understand the following explanation of the proposed study procedures. The following information describes the purpose, procedures, potential harms/risk/discomforts, and the benefits associated with this study. It also describes your right to refuse to participate or to withdraw from any part of the study at any time.

In order to decide whether you wish to participate in this research study, you should understand enough about it to make an informed decision. This is known as the informed consent process. Please ask the researcher to explain any words you do not understand before signing this consent form. Make sure all your questions have been answered to your satisfaction before signing this document.

Purpose

You have been asked to participate in a study designed to examine the physiological effects of meaning in life and mindfulness meditation. Electrocardiogram (ECG) recordings, pupillometry and respiration measurements will be taken. Research from this study will be presented at conferences and utilized for thesis requirements and future publications.

Role of Research Participant

Your participation in this study will entail a time commitment of 90 minutes. You will be granted 2.0 credits for attending the study. If you agree to participate in this study, you will be asked to provide your up-to-date medical history during the prescreening. These questions will help the researcher determine if you are eligible to participate in the study. Feel free to ask the researcher to clarify the questions, if necessary.

If you choose to partake in this study, you will be asked to complete 7 questionnaires, complete a cognitive task and listen to a 10-minute recording related to mindfulness meditation.

Questionnaires:

a. Meaning in Life Questionnaire: measures the presence and search for meaning in life
b. Meaning in Life State Scale: measures the current state of meaning in life
c. Positive and Negative Affect Schedule: assesses the two dominant dimensions of mood, positive and negative affect
d. Beck Anxiety Inventory: examines baseline anxiety levels

e. Center for Epidemiologic Studies Depression Scale: assesses depressive symptoms
f. Five Facet Mindfulness Questionnaire: measures five factors of mindfulness
g. Demographic Questionnaire

Cognitive Task:

You will be asked to solve a pattern consisting of four alphanumeric characters presented at the top of the screen that will be followed by a 5th character. You will be asked to click either "True" or "False", respectively, depending on whether or not the 5th character follows the same pattern as the previous four characters. Heart rate variability, pupillometry, and respiration measures will be taken during this task.

Listening Task:

You will be asked to sit quietly and still for 10-minutes while listening to a recording related to mindfulness meditation. Heart rate variability, pupillometry, and respiration measures will be taken during this task.

Potential Harms, Risks or Discomforts

Some of the questions ask about private matters such as whether or not you have been clinically diagnosed with a mental disorder or if you have any illnesses/diseases. To mitigate this potential risk, you may choose not to answer the question. There is no risk for undergoing pupillometry, ECG recordings or respiration measurements, however, some participants may feel uncomfortable performing a cognitively demanding task while attached to various pieces of equipment. If at any point you feel uncomfortable, please let the researcher know and you may take breaks at any point.

Potential Benefits

There are no substantial benefits associated with participating in this study. We hope this investigation will lead to a better understanding of the physiological effects of mindfulness meditation.

Voluntary Participation and Withdrawal

Your participation in this study is completely voluntary and you may choose to stop participating at any time. Your decision not to volunteer, to stop participating, or to refuse to answer particular questions will not influence the nature of the ongoing relationship with York University either now, or in the future. You will receive 2.0 URPP credits for attending this study. If you decide to stop participating, you may withdraw without penalty, financial or otherwise and you will still receive the promised inducement (2.0 URPP credits). In the event you withdraw from the study, all associated data collected will be immediately destroyed wherever possible. Should we wish to withdraw after the study you will have the option to also withdraw your data up until the analysis is complete.

Confidentiality

Unless you choose otherwise, all information you supply during the research will be held in confidence and unless you specifically indicate your consent, your name will not appear in any report or publication of the research. The experimental data acquired in this study is collected in an anonymized form that

cannot be connected back to you. This research may be used for teaching purposes, presented at meetings, published, shared with other scientific researchers, or used in future studies. Your name or other identifying information will not be used in any publication or teaching materials without your specific permission.

Data will be collected via ECG, eye-tracking glasses, respiration belt and the computer. Physiological data (ECG, pupillometry, respiration). Hand written notes will not have any identifying information. Written data will be safely stored in locked filing cabinet and only the researcher will have access to this information. Any data collected via computer will be securely stored on password protected USB keys and laptops with solely the researcher having access to this data. Electronic data will be retained on a password protected USB in a locked filing cabinet until August 2026. Handwritten notes (with no identifying information) will also be retained until August 2026 in a locked filing cabinet

Confidentiality will be provided to the fullest extent possible by law. The data collected in this research project may be used – in an anonymized form – by members of the research team in subsequent research investigations exploring similar lines of inquiry. Such projects will still undergo ethics review by the HPRC, our institutional REB. Any secondary use of anonymized data by the research team will be treated with the same degree of confidentiality and anonymity as in the original research project.

The researcher acknowledges that the host of the online survey (Survey Monkey) may automatically collect participant data without their knowledge (i.e., IP addresses). Although this information may be provided or made accessible to the researchers, it will not be used or saved without participant's consent on the researchers system. Further, because this project employs e-based collection techniques, data may be subject to access by third parties as a result of various security-based legislation now in place in many countries and thus the confidentiality and privacy of data cannot be guaranteed during web-based transmission.

Questions

If you have questions about the research in general or about your role in the study, please feel free to contact Kevin Dang by email (kvndang@my.yorku.ca) or Dr. Paul Ritvo by telephone at (416) 736-2100 ext. 22396 or by e-mail (pritvo@yorku.ca). You can also contact the department of Kinesiology and Health Science by telephone (416) 736-5728 or email (kahs@yorku.ca).

This research has received ethics review and approval by the Delegated Ethics Review Committee, which is the delegated authority to review research ethics protocols by the Human Participants Review Sub-Committee, York University's Ethics Review Board, and conforms to the standards of the Canadian Tri-Council Research Ethics guidelines. If you have any questions about this process, or about your rights as a participant in the study, please contact the Sr. Manager & Policy Advisor for the Office of Research Ethics, 5th Floor, Kaneff Tower, York University (telephone 416-736-5914 or email ore@yorku.ca).

I consent to participate in this research study, "Measuring Relations Between Meaning in Life, Stress, and Mindfulness Meditation Using Heart Rate Variability and Pupillometry" conducted by Dr. Paul Ritvo (Principal Investigator) and Kevin Dang. I have understood the nature of this project and wish to participate. I am not waiving any of my legal rights by completing this form. By entering my name below, I am indicating my consent.

Name:_____ Date:_____

Appendix G: Study Debriefing Form

Study Debriefing Form

Study Name: MEASURING RELATIONS BETWEEN MEANING IN LIFE, STRESS, AND MINDFULNESS MEDITATION USING HEART RATE VARIABILITY AND PUPILLOMETRY

PRINCIPAL INVESTIGATOR:
Kevin Dang

Purpose:
Thank you for participating in this study examining stress reactivity and recovery in individuals who report high and low meaning in life during stressful performance and mindfulness meditation. Here we explain what's known about stress and its effects on heart rate variability (HRV) and explain our hypothesis. The last page contains a list of resources that will help you learn more, if interested.

Confidentiality:
You may decide that you do not want your data used in this research. If you would like your data removed from the study and permanently deleted, please advise the experimenter. Whether you agree or do not agree to have your data used for this study, you still receive URPP credit for your participation.

Also, please do not disclose research procedures and/or hypotheses to anyone who might participate in this study in the future as this could affect the results of the study.

Protocol:
The purpose of the rest task was to obtain a baseline HRV measurement.

The purpose of the Pattern Solving Task (PST) was to induce stress in order to study it. We developed this task to assess cognitively-based stress in a situation approximating academic test-taking. We aimed to precisely evaluate the kind of stress that occurs when people, like you, face difficult exams and experience doubts about performance. Deception was absolutely necessary to arrange the test so right answers would seem possible while, in fact, they are impossible. We created the test such that 50% of answers are credited as 'correct' and 50% are credited as 'incorrect', when there are no real correct answers. Thus, your results are **not** indicative of your cognitive/intellectual abilities. This debriefing is important because we don't want you to register any experience of failure from engaging in the task. In fact, your engagement was a success as you provided us and other researchers valuable help in better understanding stress. Ultimately these understandings can be translated into ways to help people perform better under conditions of stress.

Our current published research with this protocol indicates it evokes higher stress levels, as it was designed to do, and that subjects believe that they are engaged in a test taking situation where real answers are possible and credited.

The purpose of the post-stress phase was to assess your recovery from a stressful performance under one of two conditions: (1) listening to a guided mindfulness meditation or (2) listening to a description of mindfulness meditation.

Stress:
The autonomic nervous system (ANS) controls many internal functions of the body (e.g., heart activation), and ANS imbalances are linked to mental health difficulties. The ANS is divided into two

branches: the sympathetic nervous system ("fight or flight") and the parasympathetic nervous system ("rest and digest"). Sympathetic activation is the normal physiological response under stress conditions, whereas parasympathetic activation is normally involved in stress recovery. Although some stress is inevitable even in the relative safety of day-day living, an excess stress can lead to conditions such as hypertension, myalgic pain, hyperhidrosis, and flushing.

Heart Rate Variability (HRV):
Flexible regulation of autonomic activity is essential for effective dealing with changing environmental demands. Autonomic regulation is related to HRV – a measure of interval variability between heartbeats. HRV measures were taken at rest, during the stress task and during one of the four post-stress conditions. Reduced HRV indicates a dysregulated system that is "locked" in a pattern, rather than adapting flexibly to changes in the environment. Reduced HRV has been demonstrated under conditions of worry and mental stress, and may indicate states such as low parasympathetic activity, prefrontal hypoactivity, and disease (e.g., depression, cardiovascular risk, and all-cause mortality). On the other hand, increased HRV is a sign of cardiac health and adaptability, reflecting the heart's ability to respond dynamically and efficiently to stimuli. In other words, HRV measures provide information about the integrity of the autonomic nervous system, and overall health.

Our hypotheses:
We hypothesized that people with lower ratings of meaning in life would be more sympathetically activated during the stress and mindfulness phases. We also hypothesized that guided mindfulness meditation would promote stress recovery regardless of life meaning ratings. Furthermore, we anticipated reductions in life meaning following the stress phase, and increases in life meaning following guided mindfulness meditation.

Questions:
We hope that this was a positive experience for you and that the post-stress listening intervention helped you recovery from the stressful task. If you have questions about the research in general or about your role in the study, please feel free to contact Kevin Dang (kvndang@my.yorku.ca) or Dr. Paul Ritvo by telephone at (416) 736-2100 ext. 22396 or by e-mail (pritvo@yorku.ca)

Resources:

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