Subjective Experience-Physiology Coherence

By

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Abstract

Imagine feeling intense stress: palms sweaty, heart racing, breathing shallow. Sensations of the body often come to the forefront when describing experiences of emotion or stress, yet these physiological changes are separate from the subjective 'feeling' of these states that we experience mentally. How are these mental feelings connected to the physiological responses of the body? When subjective feelings track strongly with physiological signals of the body, does this indicate adaptive functioning? Could discordance between subjective experience and physiological arousal under stress even be a marker of flawed insight, denial, or limited awareness of mental states? Is awareness of the body a prerequisite for strong coherence between subjective feelings and physiology? Can we learn to have greater coherence between our minds and bodies, and will this improve our well-being? This work focuses on coherence between subjective experience and peripheral physiological activity. I first seek to replicate initial findings showing that when subjective experience tracks more strongly with physiological signals of the body (i.e., strong subjective experience-physiology coherence) individuals tend to have higher psychological well-being, and lower anxiety and depression. I seek to clarify the construct of subjective experience-physiology coherence by examining associations with acceptance and awareness of subjective states, and how it relates to body awareness (i.e., interoceptive accuracy). Finally, I evaluate whether subjective experience-physiology coherence can be increased through a brief mindfulness meditation training as a potential mechanism through which mindfulness training increases well-being. The sample size was limited by pandemic impacts, reaching only $N = 120$ of the originally targeted $N = 260$, which in turn limited our ability to detect any significant effects, apart from the mindfulness group showing greater increases in Nonjudging of Inner Experience relative to the control group. However, this study developed two novel measurements that can be used by other studies in the future.

Introduction

States of stress and emotion are initiated by some stimulus, whether it be external (a bear) or internal (thoughts of a bear you had a tense conversation with yesterday). These stress or emotion states involve both a body state (e.g., physiological responses), and a subjective mental "feeling" state. The body state and mental state are bidirectionally related, each influencing the other (Andrews et al., 2013). There is disagreement on whether the body state or the mental state is initiated first, and it is likely that the direction differs depending on individual traits and context.

Interoception

Interoception refers to awareness of internal bodily signals. We can measure states of the body, such as cardiac activity (e.g., through an electrocardiogram), respiration (e.g., through a tension belt around the diaphragm), and electrodermal activity (i.e., sweat activity, e.g., through sensors on the palm), and we can ask people to report on their perception of these signals. By comparing individuals' reports of their body state to their measured body state, we derive a measure of interoceptive accuracy, an objective measure of how accurate an individual is at perceiving their own internal bodily signals. For example, individuals are asked to report heart beats, which are compared to the number of heart beats recorded via electrocardiogram (Schandry, 1981). In order for the measured body state and the report on the body state to align, individuals must have a level of awareness of their body state. Yet, this awareness is likely impacted by a number of factors; for example, stronger afferent signals from the body may be more easily accessible to awareness. Interoceptive accuracy is thus just one dimension of the broader concept of interoception which involves numerous distinct processes and abilities.

Taxonomy of Interoception

Several attempts have been made to parse dissociable aspects of interoception. Garfinkel et al. (2015) helpfully differentiated interoceptive accuracy (ability to accurately report on bodily states), from sensibility (beliefs about interoceptive abilities, measured through self-report), and from awareness (accuracy in reporting on one's own interoceptive abilities; termed 'insight' by others; e.g., Khalsa et al., 2018), while also providing evidence that these are distinct and dissociable dimensions of interoception. Murphy, Catmur, and Bird (2019) further differentiated interoceptive accuracy from interoceptive attention (attention given to interoceptive signals). Murphy, Catmur, and Bird (2019) also raise a key point that various facets of interoception can be measured using both objective (i.e., task-based) or self-report measurements. For example, we can ask people to report on their interoceptive accuracy, interoceptive attention, or interoceptive insight, each of these reflect a different ability and so self-evaluation of each is distinct. Khalsa and the Interoception Summit 2016 participants (2018; p. 503) presented a taxonomy of interoception which includes features of attention (”observing internal body sensations”), detection (”presence or absence of conscious report”), magnitude (”perceived intensity”), discrimination (”localize sensation to a specific channel or organ system and differentiate it from other sensations”), accuracy (sensitivity; “correct and precise monitoring”), insight (”metacognitive evaluation of experience/performance (e.g., confidence-accuracy correspondence), sensibility (”self-perceived tendency to focus on interoceptive stimuli (trait measure)”), and self report (”psychometric assessment via questionnaire (state/trait measure)”).

More recently, in perhaps the most comprehensive taxonomy yet, Suksasilp and Garfinkel (2022) parsed interoception into different dimensions (or levels of processing) and different bodily axes. Bodily axes include different organ systems such as cardiovascular, gastric, and respiratory, and dimensions can also be measured across different bodily axes. Their framework defines the following dimensions:

a) **Central neural representation** refers to central nervous system activity involved in the processing of peripheral physiological signals.

b) **Nature of afferent signals:** Signals may differ in strength and variability, both trait-like across individuals, as well as within individuals across different states. For example, some individuals on average may have stronger and more variable cardiac signals compared to others, and within an individual, cardiac signals may become stronger and more variable under stress compared to rest.

c) How **afferent signals impact preconscious** central neural representations and the **processing** of external stimuli may also differ (for example, the timing of stimulus presentation relative to the cardiac cycle impacts processing of those stimuli; Al et al., 2020).

d) **Interoceptive accuracy**[1] refers to individuals' ability to accurately report on their interoceptive signals, often measured by comparing participants' reports of their

[1]Note that participants may demonstrate interoceptive accuracy -- where their responses align with their objectively recorded physiology – despite in response to queries denying conscious awareness of their interoceptive signals. Tasks that supply response options may be particularly susceptible to dissociations between conscious awareness and measured accuracy. As in implicit reward learning tasks (e.g., Leganes-Fonteneau, Scott, & Duka, 2018; Fu, Fu, & Dienes, 2008), interoceptive signals may guide accurate response selections, even in the absence of conscious recognition of the interoceptive signals. While responses indicate accurate perception, individuals may still insist they are not able to feel, for example, their heart beats. Interoceptive accuracy measured through some tasks thus may not imply conscious awareness of interoceptive signals. This differentiation is not meant to dissociate interoceptive accuracy from interoceptive insight measures: it is not entirely captured by interoceptive insight measures, which typically query confidence about performance. Confidence ratings can also be guided by the sort of "gut feeling" (even in cardiac interoceptive accuracy tasks) that guided the responses that measured accuracy. But rather to differentiate interoceptive accuracy where individuals are consciously aware of their interoceptive signals from interoceptive accuracy where individuals are not consciously aware of the interoceptive signals.

bodily signals to their objectively recorded physiological signals. There are a variety of tasks that aim to assess interoceptive accuracy across a range of bodily axes. Focusing on cardiac interoceptive accuracy, Brener and Ring (2016) provide an in-depth comparison pointing to advantages of method of constant stimuli tasks over other cardiac interoceptive accuracy tasks, which I will briefly review here. Heartbeat counting tasks ask individuals to count their heartbeats for a given time period. Then, participant reports of the number of heartbeats are compared to the number of heartbeats measured by an electrocardiogram (Schandry, 1981). Performance on heartbeat counting tasks has been shown to be associated with beliefs about heart rate, and IQ (Ring & Brener, 1996; Brener & Ring, 2016; Murphy et al.; 2018). Heartbeat discrimination tasks ask participants to discern which stimuli are simultaneous with their heartbeats. For example, two-alternative forced choice discrimination tasks ask participants to determine which of two sets of stimuli are simultaneous with their heartbeats, with one set at a pre-determined delay assumed to be universally perceived as simultaneous. However, individual differences in the lag between the R-wave and perception of the heartbeat have been established (Yates et al., 1985; Brener & Kluvitse, 1988), thus two-alternative forced choice discrimination tasks have an elevated false negative rate for accurate perceivers because they fail to identify those who perceive their heartbeats at a different latency than the predetermined delay (Brener & Ring, 2016). Method of constant stimuli tasks present stimuli at a range of different latencies from the R-wave, thus allowing for individual differences in the delay at which the heartbeat is perceived, identifying accurate perceivers as those who can consistently identify the same delay as simultaneous.

e) **Interoceptive attention** refers to individuals' ability to attend to their interoceptive signals, which likely correlates with other attentional abilities. Interoceptive attention also refers to individuals' more habitual pattern of the degree of attention they give to interoceptive signals, or how much they tend to be aware of interoceptive signals. This category likely can be further parsed into distinct abilities.

f) **Prior beliefs and self-report** are included as one dimension. Under predictive processing frameworks, individuals' (potentially preconscious) beliefs about their bodily states work as expectations that are then compared to afferent signals from the periphery. When expectations do not match the signals, the error filters up to revise the expectations until there is agreement between signals and expectations. Expectations may also impact the signals, shifting signals to better align with expectations. **Self-report** may tap into beliefs about multiple different dimensions of interoception, for example individuals may be asked about their interoceptive accuracy or interoceptive attention. This dimension thus likely encapsulates multiple distinct constructs, as individuals are likely to vary in their beliefs about different dimensions. Anticipating the next dimension, individuals' self-evaluation of their interoceptive abilities across different dimensions may or may not align with task-based measures of their abilities in those dimensions.

g) **Interoceptive insight** refers to the degree that individuals' beliefs about their interoceptive abilities correspond to their objectively measured abilities and thus represents a metacognitive measure, for example the correlation between their confidence in their performance on an interoceptive task and their accuracy on that task. Here too, insight may differ for different interoceptive dimensions such as accuracy versus attention, or with an added meta layer to this metacognitive construct, their insight into their level of insight. Suksasilp and Garfinkel (2022) note that interoceptive attention can increase central neural activation to interoceptive signals.

h) **Attribution** of interoceptive signals is a higher order process perhaps most strongly tied to subjective experience, where interoceptive sensations are appraised or interpreted as pleasant or unpleasant, harmful or benign, and into subjective states such as emotions. For example, Erle, Mitschke, and Schultchen (2021) demonstrated that individual differences in pessimism interacted with interoceptive accuracy abilities to predict psychiatric symptoms, whereby those high on interoceptive accuracy and high on pessimism tended to have more psychiatric symptoms, implying that negative attributions to interoceptive signals negatively impact psychological well-being.

In a response to Suksasilp and Garfinkel (2022), Murphy (2022) brings up the need to additionally differentiate the propensity to use interoceptive signals:

i) Individuals may differ in their **propensity to use interoceptive signals**, or whether they tend to use information from the body to inform their internal states and higher-order cognitive processes (Murphy, 2022).

These taxonomies, while still evolving, have helped to clarify that interoception may not be a unitary construct. As noted above, some of these dimensions can be parsed further still into even more discrete processes. Individuals may differ in functioning across the different dimensions of interoception, and even within a dimension across different bodily axes. Impairments of different dimensions or in the same dimension along different bodily axes are likely to have unique impacts on emotional functioning (Khalsa et al., 2018; Suksasilp & Garfinkel, 2022). Suksasilp and Garfinkel (2022) question "is interoception best conceptualized as a latent cohesive construct with dimensions, or rather a collection of loosely related processes with no underlying unity?" They note that studies measuring interoception across multiple dimensions are needed to empirically examine relations across the dimensions and inform this question of underlying unity across dimensions. Similarly, studies should measure dimensions across multiple bodily systems to inform whether there is consistency within different dimensions across different bodily systems. Furthermore, empirical studies measuring interoception across multiple dimensions alongside measures of emotional functioning will help to not only elucidate relationships between disparate dimensions, but also how different dimensions, either uniquely or in interaction, relate to emotional well-being. While not the main focus, this project evaluates relations across the interoceptive dimensions of accuracy, self-report, insight, and attribution.

Interoceptive Attribution and Subjective Experience-Physiology Coherence

Mental States, Feelings, and Subjective Experience. Taxonomies of interoception help to clarify that the ability to accurately report on physiological signals (i.e., interoceptive accuracy) is distinct from the ability to report on subjective experience, even if subjective experiences are connected to physiological changes. Just as we can turn our attention towards sensing our body, we can also turn our attention towards the broader contents of our internal conscious experience. Our experience of subjective feelings, such as stress, sadness, or excitement, often incorporates feelings from the body, yet this is not the entire experience (Pace-Schott et al., 2019). The feeling of stress is not solely the feeling of the heart pounding and palms sweating, there is a more ambiguous mental composite that these bodily states are a part of but are not its entirety. As part of subjective experience, we might perceive *mental* busyness or blankness, cloudiness or sharpness, tension or ease, and while these feelings may be heavily influenced by physiological signals, they are distinct from pure sensations of peripheral physiology. The Human Affectome Project taskforce define feeling (Pace-Schott et al., 2019, p. 293) as "a perception/appraisal or mental representation that emerges from physiological/bodily states, processes inside (e.g., psychological processes) and outside the central nervous system, and/or environmental circumstances. However, the full range of feelings is diverse as they can emerge from emotions, levels of arousal, actions, hedonics (pleasure and pain), drives, cognitions (including perceptions/appraisals of self), motives, social interactions, and both reflective and anticipatory perspectives." They also acknowledge "A "feeling" is not a synonym for the term "emotion"…. in many instances feelings are a discernable component/constituent of an emotional response (which tends to be more complex)." Subjective experiences are more complex than mere awareness of body states, as they integrate information from not just physiological signals, but also the external environment, are filtered through learnings from past experiences, and depend on emotion vocabulary knowledge and the ability to accurately and granularly map language to feeling states (Lindquist et al., 2015; Pace-Schott et al., 2019). Pace-Schott et al. (2019, p. 293) also state "Feelings that are adaptive in nature serve as a response to help an individual interpret, detect changes in, and make sense of their circumstances at any given point in time." Subjective experiences help us to organize and condense the vast quantity and diversity of information we encounter over our lives; a type of summary represented as a category, in order to make sense of the individual data points (Feldman-Barrett, 2017).

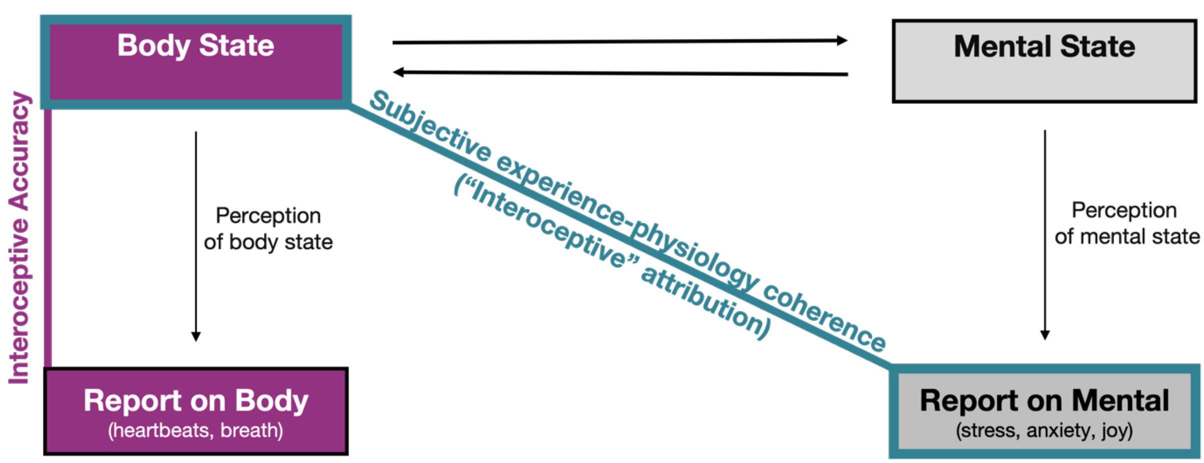
Relationship Between Interoceptive Accuracy and Subjective Experience. Emotion scientists have long assumed that awareness of physiological signals informs awareness of subjective states such as emotions (e.g., James, 1894). Recent support for this assumption often relies on overlap in neural correlates of the functions of sensing the body and more complex subjective experiences (Harrison et al., 2010; Terasawa et al., 2011). There has been some more direct evidence supporting a connection between alexithymia (impaired ability to recognize emotions) and interoceptive accuracy. For example, Bornemann and Singer (2017) used a heartbeat counting task to measure interoceptive accuracy and the Toronto Alexithymia Scale (TAS-20; Bagby, Parker, & Taylor, 1994) to assess alexithymia, each with repeated assessments across a 9-month intervention. They found an inverse association between change in interoceptive accuracy and change in alexithymia from the first timepoint to the second. However, they did not find a significant association between interoceptive accuracy and alexithymia at baseline, the only significant association was between changes in measures. Stronger evidence comes from a recent meta-analysis showing no association between interoceptive accuracy measured via tasks and alexithymia (Trevisan et al., 2019). Awareness of subjective experiences may not be dependent on conscious awareness of states of the body (interoceptive accuracy): physiological state information could be incorporated outside of awareness. Pace-Schott et al. (2019, p. 294) explain "The integrated output of multiple physiological systems may provide highly complex inputs to central mechanisms that produce the conscious experience of feelings, moods and emotions. And such inputs may be modified by efferent signals at each level of the neuraxis. Thus, the many physiological influences on emotion may acquire specificity only when integrated with one another at the level of the brainstem or forebrain," supporting the possibility that individuals are able to observe mental experiences without awareness of any corresponding physiological signals from the periphery, which are integrated at a lower level. For example, individuals can accurately report on the weather without awareness and understanding of the multiple forces behind the weather, and still their reports on the changes in the weather they perceive would correlate with changes in these forces. Similarly, they may report on their stress or nervousness without awareness or understanding of the numerous physiological changes that have occurred alongside these mental feelings, e.g., that their heart rate has increased, or their palms are sweating, and still their reports of their subjective experience and their peripheral physiological activity would align. It is as-of-yet undetermined whether awareness of subjective mental states necessarily requires awareness of the physiology.

Furthermore, even if awareness of physiology is necessary for awareness of subjective mental states, the mental subjective feeling still involves the added step of *interpretation* or *appraisal* of physiological signals. This step of inferring what the body states mean for the more complex mental composite given context, past experiences, and language, is critical. Simply being aware of our physiological signals is unlikely to be helpful, especially if errors arise in interpreting them. If one is astutely in tune with every beat of their heart and the precise volume of breath in their lungs at each moment, but fails to translate these signals in a way that maps appropriately to larger context, what good is that bodily information? Subjective mental states help to categorize our experience and connect it to past experiences, motivate behavior, and communicate it to others in our social world. Appropriate mapping of physiological signals to our subjective experience is more relevant to functioning than awareness of raw, uninterpreted physiological signals.

Subjective Experience-Physiology Coherence. One measure of the mapping from physiological signals to subjective experience is the degree of coherence between objectively recorded physiological activity and reports of subjective experience. Figure 1 depicts the relationship and difference between interoceptive accuracy and subjective experience-physiology coherence. One example of subjective experience-physiology coherence is the within-person association between subjective stress and heart rate during experiences of stress, termed "subjective stress-heart rate coherence," (Sommerfeldt et al., 2019). Participants undergo a stress induction procedure involving phases with different intensities of stress. Across the different phases, cardiac activity is objectively recorded via an electrocardiogram, and participants are asked to self-report their perceived level of stress at multiple timepoints, resulting in multiple within-person data points of subjective stress, and corresponding data points of physiological arousal. Individual differences in the strength of the association between heart rate and reports of subjective stress are represented by subjective stress-heart rate coherence. Broad definitions of interoception (Khalsa et al., 2018; Suksasilp & Garfinkel, 2022) may classify subjective experience-physiology coherence as interoceptive attribution.

Figure 1

Differentiating Interoceptive Accuracy from Subjective Experience-Physiology Coherence



Note. While the body state can be objectively measured and thereby compared to reports on the body state to derive a measure of interoceptive accuracy, the mental state cannot be directly objectively measured, it is by nature a subjective experience accessible only to the one experiencing it, and so we have no measure of accuracy in perceiving mental states.

Few studies have investigated the association between interoceptive dimensions and subjective experience-physiology coherence. One exception is the examination of relations between self-reported interoceptive ability (via the Body Awareness Questionnaire; Shields et al., 1989) and coherence between subjective valence and heart period by Muhtadie (2017). In a sample of $N = 56$, Muhtadie (2017) demonstrated a significant positive association between subjective valence-heart period coherence and self-reported interoceptive ability. Sze et al. (2010) also examined coherence between subjective valence and heart period in a sample of $N = 63$ Vipassana meditators ($N = 21$), dancers ($N = 21$) and controls with no formal meditation or dance training, or participation in other body-focused activities ($N = 21$). They found subjective valence-heart period coherence to be significantly stronger in meditators and dancers (i.e., groups with body-awareness training), compared to controls. Both studies provide evidence supporting an association between more body awareness and stronger subjective experience-physiology coherence, however, neither objectively measured interoceptive accuracy using a task-based measure.

Acceptance. Coherence between subjective experience and physiology requires awareness of subjective states, as without awareness it would not be possible to report on subjective experience. Even if there is awareness, if there is a lack of acceptance of the subjective state, this is likely to lead to imprecise reports of the subjective experience, and a mismatch with physiology. Individuals who do not accept their mental states are unlikely to disclose them on self-reports. For example, some individuals tend to cope with feelings by denying the reality of the sources of those feelings or denying the feelings themselves. Individuals who use this denial style of coping are unlikely to report their feelings in a way that tracks with their physiology, as they are refusing to accept the feelings are real. Suppression has also been shown to have differential impacts on physiological responses versus subjective experiences (Hofmann et al., 2009), so attempts to suppress would also disrupt coherence between physiology and subjective experience. Similarly, some individuals may avoid facing or paying attention to their feelings, which may be thought of as a lack of acceptance of feelings. Lack of acceptance is likely to lead to discordance between physiological responses and self-reports of subjective experience, in so far as lack of acceptance impedes valid reporting of subjective experience.

Interoception and Coherence According to the Active Inference Framework

Active inference proposes that perception is an interaction between our expectations and evidence from external stimuli (Paulus et al., 2019). The classical stimulus-response model holds that the brain's reaction to external or internal stimuli leads to experience. In contrast, active inference accords that the brain instead constantly formulates predictions for what stimuli will be, then actively samples data from sensory signals to maximize evidence for the prediction. When there is a discrepancy between predictions and sensory information from the external world, a 'prediction error' occurs, providing a feedback signal to higher order processing to update predictions. A new and improved prediction is thus generated, incorporating the updated information, and this process repeats until prediction errors (i.e., conflicts) between expectations and reality are minimized. This rapid unconscious process results in the best prediction becoming perception or experience. Perceptions are thus a compromise between what we believe and incoming evidence, and so are constructed by the brain – lending this framework to also be referred to as “constructionist” (Feldman-Barrett, 2017).

Active inference applied to interoception more specifically proposes that our brains have an internal model, or expectations, of what we will feel from our body. It compares this internal model to incoming sensory signals from peripheral physiology, updating the model to match the incoming signals as necessary (Feldman-Barrett, 2017; Paulus et al., 2019). Expectations do not merely forecast upcoming stimuli from the external environment, but also project impending internal sensations. Interoception is unique in that the physiological systems generating the sensory signals can also be modified by the expectations through brain-body connections (Paulus et al., 2019). This is distinct from perception of the external world, where the stimuli being perceived cannot be directly modified by the brain’s expectations about those stimuli. Paulus, Feinstein, and Khalsa (2019, p. 5) describe how this interaction between the brain and body can work to help minimize prediction errors:

> “In an adaptive individual, corrective action in the presence of somatic error can be achieved by adjusting expectations (priors) to match the current physiological state or by engaging in regulatory actions that change the afferent signal, leading the current physiological state to conform more closely with expectations. In either case, successful corrective action reduces somatic error, resulting in homeostatic balance within the nervous system.”

Coherence between self-reported subjective experience and physiological responses would thus constitute adaptive functioning, whereby there is agreement between the physiology that constitutes sensory signals and individuals’ expectations of those signals, indexed by their self-reported subjective experience. This fits with previous findings linking strong coherence between self-reported subjective experience and physiology to well-being, an indicator of adaptive functioning (Sommerfeldt et al., 2019; Sommerfeldt et al., in prep; Brown et al., 2019).

I previously investigated 1,065 participants from the MIDUS 2 study (www.midus.wisc.edu) who completed a self-report battery and a stress-induction procedure involving computerized cognitive stressor tasks while physiological and self-report measures of stress were repeatedly recorded (Sommerfeldt et al., 2019). Individual differences in the association between self-reported stress and heart rate were analyzed in relation to measures that reflect psychological well-being. The within-person association between self-reported stress and heart rate (subjective stress-heart rate coherence) was significantly associated with higher psychological well-being (PWB; Ryff, 1989). Focusing on psychological well-being in the same sample examined by Sze et al. (2010; N = 63 of meditators, dancers, and controls), Brown et al. (2019) also found subjective valence-heart period coherence to be associated with higher subjective well-being (Satisfaction With Life Scale [SWLS]; Diener, Emmons, Larsen, & Griffin, 1985). The context in which subjective experience-heart activity coherence was measured in the Brown et al. (2019) and Sommerfeldt et al. (2019) studies was different. Brown et al. (2019) examined subjective experience along the general valence continuum of very negative to very positive in response to emotion-eliciting films, and Sommerfeldt et al. (2019) examined subjective stress levels in response to computerized cognitive stressor tasks (the Stroop task, Stroop, 1935; and the Morgan And Turner Hewitt [MATH] task, Turner et al., 1986; Turner, Sims, Carroll, Morgan, & Hewitt, 1987). Results across these two studies support the generalization that strong associations between subjective experience, be it emotion or stress, and heart rate, are linked to higher well-being.

Interoception and Coherence Relations to Mental Health

Whereas adaptive functioning would result in updating expectations to better match evidence from the senses to reduce error signals, in psychopathology, unmatched expectations may perseverate. Paulus, Feinstein, and Khalsa (2019) hypothesize that psychopathology is the result of a) unusually strong expectations of what elicits physiological changes and b) problems with adjusting these expectations when the environment changes (i.e., a lack of flexibility in adjusting with different contexts). Beliefs are biased in a particular direction, and they don't update according to evidence, resulting in persistent error signals.

In line with Paulus et al.'s hypothesis, the previously mentioned Sommerfeldt et al. (2019) and Brown et al. (2019) studies also demonstrated that discordance between physiological signals and interpretations (self-reports of subjective experience, including both stress and positive/negative affect) was associated with higher depression and anxiety. Sommerfeldt et al. (2019) found coherence between self-reported stress and heart rate to be tied to fewer depressive symptoms on the Center for Epidemiological Studies Depression Inventory (Radloff, 1977) and lower trait anxiety on the State Trait Anxiety Questionnaire (STAI; Spielberger, Gorsuch, Lushene, Vagg, & Jacobs, 1983), while Brown et al., (2019) found coherence between self-reported valence and heart rate to be tied to fewer depressive symptoms on the Beck Depression Inventory – II (BDI; Beck, Steer, & Brown, 1996), as well as lower trait anxiety on the STAI.

Lack of coherence between subjective experience and physiology may represent a mismatch between the brain's expectations or interpretations and data from peripheral physiology. The expectations discussed in the active inference framework are thought to function largely outside of awareness, rising to the level of awareness as a perception once prediction errors are minimized. Yet, according to Paulus et al. (2019)'s hypothesis of interoceptive functioning in psychopathology, persistently biased expectations do not update according to incoming data, and so would rise to the level of awareness despite persisting prediction errors, potentially as subjective mental feeling states that are perceived and reported. This framework aligns with conceptualizations of depression from Cognitive Behavioral Therapy – whereby cognitive biases (which would impact internal models/expectations) negatively color perceptions of past, present, and future events (Beck, 2002; Hertel & Mathews, 2011).

Coherence and other measures of "interoceptive attribution," uniquely include reports of subjective feeling states and involve a metacognitive aspect of reflecting on our own mental feelings and states. While past work has theorized that interoceptive accuracy is an important contributor to emotional regulation and psychopathology (Murphy et al., 2017), simply being aware of physiological signals is unlikely the critical step in this process. And indeed, past work has shown that high interoceptive accuracy can be maladaptive (Domschke et al., 2010). The attribution step, where interoceptive signals are (consciously or unconsciously) interpreted to subjective experience is a critical step where errors are likely to impact emotional functioning and well-being -- the affective flavoring that the higher-order processing adds on to raw physiological cues. This is where things likely go awry in ways that detrimentally impact our well-being. We can be wholly connected and in tune with our physiological signals but appraising them in exaggerated or as harmful when they are benign.

Mindfulness

Mindfulness may help to improve interoceptive attribution abilities, and perhaps through doing so positively impact well-being and ameliorate symptoms of anxiety and depression. Like interoception, mindfulness is a broad concept with many dimensions, both according to academic scientific conceptualizations, as well as traditional Buddhist ones from which mindfulness is appropriated (Lutz et al., 2015, Dunne, 2015). Academic scientific conceptualizations have permeated popular culture; one study exploring "lay" definitions of mindfulness from 326 meditators found their definitions to align with those from academic contexts, including references to attention/awareness, a non-evaluative stance, a strategy (to regulate emotions, the mind, or attention), psycho-affective spiritual state, and personal development (Alvear, Soler, & Cebolla, 2022). Alvear, Soler, and Cebolla (2022)'s examination of lay definitions of mindfulness anticipates my own evaluation of lay definitions of stress later in this work.

What is Mindfulness?

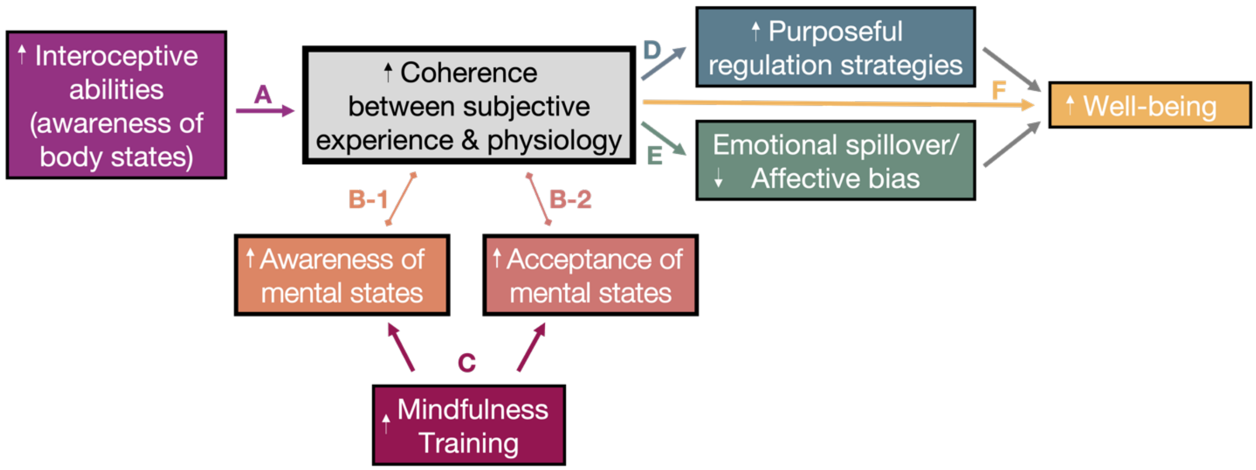
Mindfulness is perhaps most often defined using a description from Jon Kabat-Zinn (1994, p.4) "pay attention in a particular way: on purpose, in the present moment, and non-judgmentally." Bishop et al (2004) describe a more trait-like two component model of mindfulness, "The first component involves the self-regulation of attention so that it is maintained on immediate experience, thereby allowing for increased recognition of mental events in the present moment. The second component involves adopting a particular orientation toward one's experiences in the present moment, an orientation that is characterized by curiosity, openness, and acceptance."

Lutz, Jha, Dunne, and Saron (2015) describe different features of mindfulness as continua along three primary dimensions: a) object orientation (whether an experience is oriented toward an object/class of objects), b) dereification (degree to which mental phenomena such as thoughts, feelings, and perceptions are interpreted as mental phenomena versus accurate representations of reality), and c) meta-awareness (monitoring of mental experience, specifically including "background awareness" of other aspects of mental experience beyond the object of focus); and four secondary qualities: a) aperture (broadness or narrowness of focus), b) clarity (vividness), c) stability (persistence over time), and d) effort (ease or difficulty to sustain).

The impacts of mindfulness training will depend on the specific training involved (Lutz et al., 2015). For example, Lutz et al., 2015 compared Focused Attention and Open Monitoring practices. In Focused Attention practices, the aperture of attention is narrowly focused on a specific object, such as the breath. When distractions occur, such as thoughts that interfere with the observation of the breath, the instruction is to recognize the distraction, sometimes mentally label the distraction (such as "thought"), and reorient attention to the breath. The practice of recognizing distractions is thought to develop meta-awareness and dereification, as it requires attending to cognitive processes, observing them as objects, and separating from them. Open Monitoring involves a broader aperture of attention, not focused on any one object but observing all sensations and perceptions of each moment. Open Monitoring is instructed to be practiced with relaxed effort, as effort may narrow the aperture of attention to a singular object, leading to alternating the spotlight of attention to focus on each of the many sensations and perceptions of each moment in turn. The practice is instead of releasing effort, broadening the aperture of attention, allowing observations to fall into awareness, without weighting any one perception more than others, giving all equal weight in each moment. Trainings that include attention to and observation of mental contents are likely to increase awareness of subjective experience. Trainings that incorporate practice of adopting a non-judgmental stance to what is observed in the mind are likely to increase acceptance of subjective experiences.

Figure 2

Overarching Framework of Relations Between Study Variables



Note. A) Interoceptive abilities (accuracy, insight, and self-reported) is thought to be (on average) associated with stronger coherence between subjective experience and physiology, as awareness of the body is likely to contribute to awareness of subjective experience (although note I do not think it is *necessary* for awareness of subjective experience, as one can be aware of mental contents without awareness of physiology that informed those mental contents outside of conscious awareness). B-1) Coherence involves awareness of mental states. B-2) Coherence involves acceptance of mental states. C) Mindfulness training is likely to increase both acceptance and awareness of mental states, and so increase coherence. D) Recognition of mental states is likely to increase purposeful stress regulation strategies, as one much first recognize a state to regulate in order to initiate purposeful regulation. E) Coherence is likely to decrease emotional spillover as past work has shown that awareness of states decreases the degree that they spillover to bias interpretation of unrelated stimuli (Lapate et al., 2014). Association between coherence and emotional spillover may also reflect a more general underlying tendency towards inflexible and biased expectations that do not update according to incoming data, per the active inference framework. F) Employment of purposeful regulation strategies and decreased emotional spillover over time will contribute to higher well-being, both in terms of more positive aspects of well-being, as well as reductions in symptoms detrimental to well-being, such as those of depression and anxiety.

The Current Study

The current study sought to evaluate features of the overarching framework (Figure 2).

Stress

I chose to study stress as the subjective experience corresponding to physiological activity for coherence assessment. Stress may vary in valence, including eustress or distress (Selye, 1975). However, whether positive or negatively valenced, stress is associated with arousal, whereby higher intensities of stress and are associated with heightened arousal. Considering stress in the context of coherence simplifies interpretation of associations, as increased stress should be associated with increased physiological arousal. In contrast, there is disagreement about specific physiological responses tied to different emotions. For example, Siegel et al. (2018) conducted a meta-analysis of 202 studies that involved measurement of autonomic nervous system reactivity during laboratory-based emotion induction in adults, and did not find evidence to support physiological signatures specific to different emotions. Lack of clear physiological signatures complicates the measurement and interpretation of coherence between physiological activity and reports of emotions. Furthermore, while there is some variation in stimuli that elicit stress for different people, there is perhaps less variation relative to specific emotions. Another alternative would be asking individuals to report directly on their level of arousal, but the concept of arousal is understood differently in lay terms. Participants would have to learn the definition of arousal we would like them to use, then perform the task of evaluating that newly learned concept in themselves during the measurement procedure, increasing cognitive load and presenting a confound of learning. Studying the subjective experience of stress is advantaged by lay conceptualizations including the element of increased arousal, thus supporting a clearer expected association with physiological activity. Since definitions of stress can still vary, we also collected data on participants' definitions of stress they were considering in reporting on their subjective experience.

I chose an ecologically valid social stressor, the Trier Social Stress Test (Kirschbaum, 1993), augmenting the classic procedure with the collection of repeated self-reports of subjective stress, and continuous physiological recordings of cardiac, electrodermal, and respiratory activity. The density of self-report assessments was balanced between interfering with the response itself through too frequent queries, and a high number of data points per participant for more precise measurement of within-person coherence.

Aims of the Study

1) Conceptually replicate and extend previous findings linking subjective stress-heart rate coherence to well-being. I predicted that my original findings (Sommerfeldt et al., 2019) linking greater stress-heart rate coherence to higher psychological well-being, fewer depressive symptoms, lower trait anxiety, and less use of denial coping, would conceptually replicate with the new procedure specifically designed to measure coherence. I sought to extend these findings by evaluating associations between subjective stress-heart rate coherence and multiple measures of a) awareness of mental states and b) acceptance of mental states, where I predicted positive associations.

2) Assess whether interoceptive abilities are associated with subjective stress-heart rate coherence. In addition to completing the novel subjective stress-physiology coherence procedure, participants completed an established method of constant stimuli task (Brener, Ring, & Liu, 1994) to assess interoceptive accuracy. I augmented the original task by also including trial-level confidence ratings to allow for measurement of interoceptive insight. Participants also completed a self-report measure of interoception abilities. I predicted that higher interoceptive accuracy, insight, and self-report would be positively associated with subjective stress-heart rate coherence.

3) Determine whether stress-physiology coherence can be increased through a brief mindfulness training intervention. After a baseline study visit, participants were randomized to either a mindfulness intervention group or a control group where they recorded their screen time. Participants in the mindfulness group were assigned to listen to brief audio recordings involving mindfulness each day for a month. Participants returned for a second study visit where they again completed the protocol designed to assess stress-physiology coherence, in order to assess changes following the mindfulness intervention. I predicted that participants in the mindfulness intervention group would demonstrate greater increases in subjective stress-heart rate coherence from pre-test to post-test compared to participants in the control group. I also predicted that participants in the mindfulness intervention group would demonstrate greater increases in awareness and acceptance of subjective states from pre-test to post-test compared to participants in the control group. Given measurement of subjective experience-heart rate coherence across multiple timepoints, I also sought to assess test-retest reliability of coherence.

Methods

Participants

Participants were recruited from Madison, Wisconsin and surrounding communities through email solicitation and flyers posted on community boards, for example at area stores, restaurants, laundromats, community centers, churches, and libraries. Participants recruited were a) between the ages of 18 to 65 years old; b) comfortable reading, writing and conversing in

English; c) had access to a smartphone; d) limited experience with meditation or mindfulness (defined as less than 50 lifetime meditation or mindfulness practice hours and less than 5 in the past year), and mind-body practices (e.g., such as yoga, tai chi, or qi gong; defined as less than 100 lifetime mind-body practice hours and less than 10 hours in the past year); e) not diagnosed with current or past psychotic disorder, Bipolar Disorder, PTSD, or social phobia; f) not currently experiencing severe depressive or anxiety symptoms (defined as PHQ-8 less than 17 or GAD-7 score less than 15, respectively – this was in order to minimize adverse reactions to the stress test; Kroenke, Spitzer, & Williams, 2001; Spitzer et al., 2006); g) not currently or in the past month using prescription stimulant, beta-blocker, beta-agonist, anti-high blood pressure, or anti-anxiety medications; h) were not currently pregnant (due to physiological changes); i) not affected by a neurological disorder; j) not currently diagnosed with high blood pressure or a heart murmur; k) not using a pacemaker; l) not previously exposed to the stress test. Participants were compensated up to $75 for completing both study visits and the at-home activities ($25 for baseline visit, $35 for post-test visit, with a $15 bonus for attending both study visits and the at-home activities).

Study advertisements described the study as a "Well-Being and Stress Study" that was examining the relationship between responses to stress and well-being. Documents, including the consent form, presented the at-home activities in a balanced way, saying that participants would either be asked to record their screen time or listen to audio recordings on wellness each day for four weeks between visits.

The target sample size based on power analyses to detect small effects was $N = 260$, however meeting this target was obstructed by impacts of the COVID-19 pandemic. Data collection began in January 2020, paused during the pandemic from mid-March 2020 through

November 2021, and completed in November 2022. From January to March 2020, *N* = 23 participants completed their initial study visit, and *N* = 13 completed their post-test study visit. An additional *N* = 4 participants completed the questionnaires from the post-test visit online, from home, during the pandemic shutdown. Between November 2021 and November 2022, an additional *N* = 97 participants completed their initial study visit, and *N* = 77 completed the post-test visit. All together, *N* = 120 people participated in the study, of whom 78.3% (*N* = 94) completed post-test measures (*N* = 4 were only online questionnaires due to pandemic restrictions; *N* = 90 returned in-person). Participants ranged in age from 18-65 years old, with a mean age of 34.5 years (*SD* = 13.5 years). 78% of participants identified as White, 11% as Asian, 4% as Multiracial, 1% as American Indian or Alaska Native, 1% as Black or African American. 70% of participants identified as Women, 4% as Nonbinary, and 25% as Men.

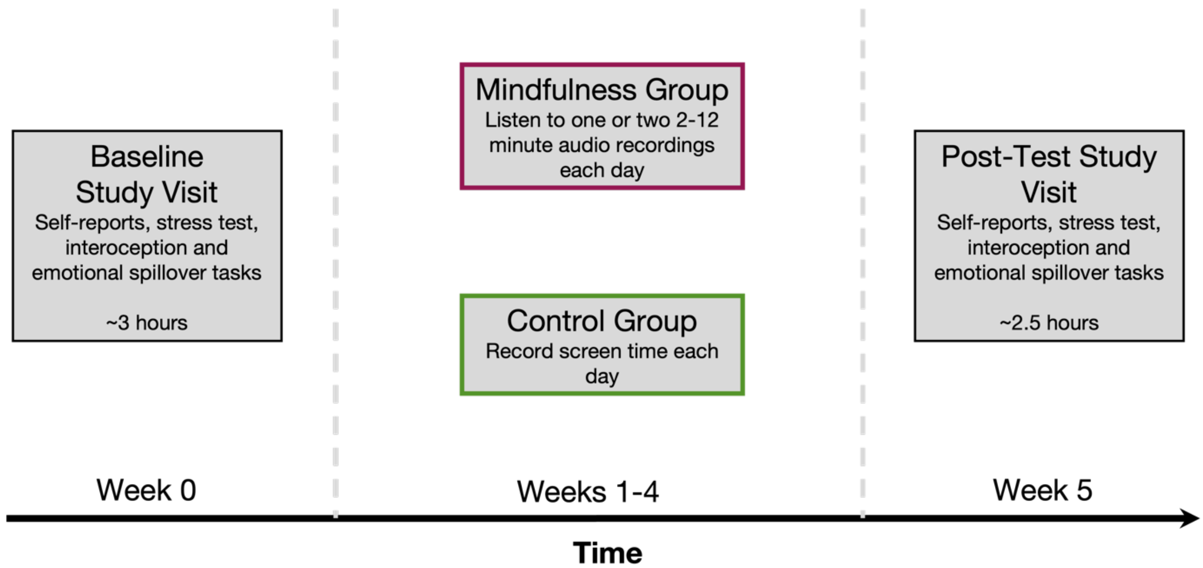
Procedure

Participants completed two study visits separated by four weeks. Each study visit involved surveys (approximately 1 hour), a neutral faces task pre-TSST (5 minutes), the TSST (approximately 35 minutes), a neutral faces task post-TSST (5 minutes), and the method of constant stimuli task (approximately 30 minutes). Participants completed all study measures at both timepoints except for some minor differences in surveys. For example the post-test study visit did not assess demographic and socioeconomic status information, or general health information unless they responded that it had changed significantly between visits.

Each study visit lasted approximately 3 hours, with the second visit slightly shorter due to fewer measures. Study visits were scheduled for later afternoon/evening, from 2-5pm or 5-8pm, with the goal of perturbing stress at the time of day when stress hormones such as cortisol are lower, so increases are more observable. We aimed to have each participant complete their visits at the same time of day, on the same day of the week, exactly 4-weeks apart, in hopes that daily activities preceding the visit may be somewhat similar if participants have a regular schedule. For participants with menstrual cycles, we also aimed for the timing of each data collection session to occur during the same phase of their cycle, due to past studies showing an impact of menstrual cycle phase on coherence (Duchesne & Pruessner, 2013).

Figure 3

Broad Overview of Study Design



Intervention

At the end of the first study visit, participants were randomly assigned to a brief mindfulness training or a control group that recorded screen time.

For the mindfulness training group, training involved listening to brief audio recordings that consisted of psychoeducation and guided mindfulness practices. Audio recordings were delivered through a customized version of the Healthy Minds Program application for smartphones (https://hminnovations.org/meditation-app; Goldberg et al., 2020; Dahl et al., 2020). The contents of recordings were specifically selected to focus on self-awareness, awareness of thoughts and emotions, and acceptance of mental states. Practices included focused attention practices (e.g., awareness of the breath) and open monitoring practices. Psychoeducation included content such as information on establishing healthy habits, such as setting a low barrier goal of short practices each day, setting practice goals for each week, planning specific times and places to practice, and connecting practice to another already-established habit. Psychoeducation also included information from scientific studies, such as a description of a study showing that people spend much of their time mind-wandering, and that mind wandering was associated with unhappiness (Killingsworth & Gilbert, 2019).

Participants were instructed to listen to recordings once each day for a target of 4 weeks between their study visits. Most days included a psychoeducation component followed by a guided practice, with a few days consisting of only a guided practice. The application naturally guided participants through a sequence of recordings split up by week (with 4 different weeks) and labeled Day 1 – Day 28; participants were instructed to follow the natural order. Several of the guided practice recordings allowed participants to choose from multiple time lengths (from 5 minutes to 30 minutes, in increments of 5 minutes), and between seated or active practices. Active practices were first explained through a psychoeducation recording as practices that could be completed while walking, or while completing house chores that are not very mentally active, such as doing the dishes. Participants could choose to have the application remind them to listen to a recording each day. Researchers also monitored participants' progress during the intervention and contacted participants by phone or email if they fell behind to remind them to listen to a recording each day. The length of audio recordings for the entire 4-week training total approximately 5 hours and 10 minutes if participants select the 5-minute option (i.e., shortest option) when allowed to choose the length. The application recorded data on when and for how long participants listened to recordings, which recordings, and whether the participant chose seated or active practice. Participants were also instructed to record in a paper log the date, time, and a brief description of the practice they listened to each day.

Control participants were tasked with recording on a paper log how much time they spent on their smartphone each day for the 4-week treatment period as a sort of sham intervention. Experimenters walked control participants through where to find screen time data on their smartphone and how to set a daily reminder on their phone to record their screen time each day.

All experimenters interacting with the participant during data collection, including TSST judges, were blinded to participant groups. Each session involved 4 experimenters to make this possible: a lead data collector, assistant data collector, and two social stress test judges. The assistant data collector would become unblinded at the very end of the first session (after all measures were complete) to walk the participant through their homework activity. The assistant data collector for the baseline session was thus unblinded to that participants' group, so was never involved in the same participant's post-test session. A separate team of students ("Recruitment Team") handled all participant contact when participants were not at the lab, thus ensuring any incoming questions about homework did not unblind data collectors who could be involved with the post-test visit ("Testing Team"). As the data analyst, I was blinded to participant groups until after analyses were completed. I played the role of lead data collector for most sessions.

Stress-Induction Procedure: Modified Trier Social Stress Test (TSST)

Participants completed a version of the TSST (Kirschbaum, 1993), modified to assess stress-physiology coherence. This version of the TSST consisted of a 5-minute baseline, 5-minute speech preparation period ("prep"), 5-minute speech presentation, 5-minute math task, and 10-minute recovery period. Electrocardiogram (ECG), respiratory, and electrodermal activity (EDA) were measured continuously using the BioNomadix mobile recording suite (https://www.biopac.com/product-category/research/bionomadix-wireless-physiology/).

Two speech and two math conditions were counterbalanced across sessions. Speech conditions included a) an interview for their ideal job, and b) a candidate forum for a political office. Math conditions included a) beginning at 2043 and counting backwards in increments of 17; and b) beginning at 5 and adding 3 to, then multiplying by 2, each resulting number. Each time a participant made a mistake on the math task they were asked to begin again at the starting number.

Judges were undergraduate research assistants wearing white lab coats, trained to follow scripts, not provide any positive feedback (e.g., nodding, smiling), and appear to take notes on the participants' performance. Participants were told judges were "well trained at interpreting body language." Judge panels included one woman-identifying and one man-identifying judge for each session and judges were the same for pre- and post-test sessions for each participant, except for a few occasions with staffing issues.

The judge who identified as the gender opposite of that of the participant was the judge to communicate instructions for that session. If the participant identified as non-binary, judges flipped a coin to determine who would communicate instructions. Judges entered the room after the baseline period, and departed after the math task. The lead experimenter for the session was present for baseline and recovery periods only. The participant did not interact with the judges except in this context.

A large video camera was pointed at the participant, and a microphone was positioned on a stand in front of the participant. Participants were told the speech and math tasks were recorded for later analysis. They were not in fact recorded, which participants were debriefed on after their second study visit. Participants remained standing on anti-fatigue mats positioned near a standing-height table and the microphone for the entire procedure.

Stress Self-Reports

Before the baseline period, the lead experimenter explained and guided the participant through completing a 100 mm visual analog scale (VAS) to rate their current level of stress on a scale of 0 = not at all stressed, to 100 = extremely stressed. Participants were told they would periodically be prompted to complete a VAS stress rating during the procedure. They were prompted at 12 timepoints during the TSST: at 2 minutes, and at 4 minutes and 30 seconds into each of the 5-minute periods, and at 2 minutes, at 4 minutes 30 seconds, at 7 minutes, and at 9 minutes 30 seconds into the 10-minute recovery period. The experimenter or judge would indicate it was time to complete a form by saying "Please complete a form." The timings of self-reports were designed to balance aims to a) capture the timing of self-reports in the MIDUS biomarker project (which occurred 20-30 seconds before the end of each period), b) acquire a greater density of self-reports to increase the number of datapoints for use in within-individual stress-physiology coherence calculations, and c) not interfere with the stressfulness of the task.

Electrocardiogram (ECG)

Cardiac activity was recorded using a three-lead ECG (Biopac EL503 electrodes, GEL100, and custom ordered BN-EL45-LEAD3 modified by Biopac to be 90 cm in length instead of 45 cm) and the Bionomadix mobile recording suite.

ECG data from the TSST were processed using QRSTool (Allen, Chambers, & Towers, 2010) using a threshold followed by manual inspection and corrections by trained undergraduate research assistants as necessary to identify R-Waves. Before moving on to processing data that would be used for analyses, undergraduates had to first pass an ECG training test that involved processing data for 3-10 practice participants and comparison of their processing to mine (one group of students had to have ICC > .75 for 10 participants, and a second group of students had to have nearly identical histograms and IBI dot plots for 3 participants as described below). Following processing in QRSTool, I generated plots in R for quality assessment, including a) histograms of all interbeat-intervals (IBIs) for each participant for each phase of the TSST (5 histograms per participant), and b) dot plots of IBIs in the order they occurred in the timeseries. For processed ECG data, I visually inspected all histograms for IBIs that were separated from the distribution of IBIs for that participant for that phase. When these outlier IBIs occurred, I reviewed the context that they occurred in the timeseries using the other plot and returning to the data in QRSTool, and flagged data that needed further review. I and undergraduates most experienced with ECG processing reviewed and made corrections to those flagged timeseries as necessary. CMETX (Allen, Chambers, & Towers, 2010) calculated summary metrics on the final timeseries, including average heart rate for the 2 minutes before and 30 seconds after each stress self-report that is used in coherence.

Method of Constant Stimuli Task

Participants completed an adapted version of the Method of Constant Stimuli (MCS) familiarization task used by Brener, Liu, and Ring (1993; Brener, Ring, & Liu, 1994). The task was implemented using an Elegoo UNO R3 Controller Board with firmware that I programmed in the Arduino programming language, with assistance from John Koger (who also had the idea of using an Arduino for this task). The UNO R3 was fitted with LEDs and an active buzzer for task stimuli, with the controller board and buzzer encased in a small gray plastic box and LEDs fitted in a row through holes along the top of the box (See Appendix E). Only a single green LED was used during the task as a stimulus. The box was placed just in front of, and underneath the computer monitor. The UNO R3 was connected to a Biopac MP160 ECG amplifier through an out-ISO. The amplifier was set to R-Wave mode to accentuate R-waves over other aspects of the cardiac signal. Participants' cardiac activity was recorded using a three-lead ECG (Biopac EL503 electrodes, GEL100, and LEAD110S-W, LEAD110S-R, and LEAD110).

I programmed the task in Python using the PsychoPy library. Participants were guided through task instructions by experimenters. Participants responded using a number keypad with keys arranged such that 1, 2, 3, and 4 keys were in a single row, and the + and – keys were next to each other.

Time constraints and technical issues prevented completion of the Method of Constant Stimuli task for all participants, $N = 106$ participants completed the task at Baseline.

Light-Tone Trials

The first part of the Method of Constant Stimuli task focused on the simultaneity of visual light and auditory tone stimuli. For each trial, participants observed a series of five LED light flashes, each followed by a tone. The lag between the light and tone was the same within a trial but varied across trials. The five stimuli pairs per trial allowed for sufficient examples for participants to determine simultaneity (Brener, Ring, & Liu, 1994). There were six different delay conditions: 0 ms, 100 ms, 200 ms, 300 ms, 400 ms, or 500 ms. Delays were pseudorandomly ordered across trials.

After each trial, participants were asked to report whether the tones occurred at the same time as the lights (with 2 response options: a) yes, at the same time or b) no, not at the same time). Participants were then asked to rate their confidence in their response on a likert scale ranging from 1 = not at all confident to 4 = completely confident. Participants completed six practice trials to confirm they understood instructions before beginning the task.

As this portion of the task was originally intended as an orientation to the interoception portion of the task, the frequency and variability of the stimuli was designed to be similar to the later interoceptive stimuli. Thus, LED lights coincided with the R-wave of participants' cardiac cycle.

Light-Tone Accuracy. For light-tone trials, I expected confidence to scale with the distance from the 0 ms delay. I thus calculated accuracy with 6 levels corresponding to the 6 different delay conditions, scaled such that responses of simultaneous at the 0 ms delay were considered highly accurate, and responses of simultaneous at the 500 ms delay were considered least accurate. Similarly, responses of not-simultaneous at the 0 ms delay were considered least accurate, and responses of not-simultaneous at the 500 ms delay were considered highly accurate. Comprehensively, for trials where participants responded the lights and tones were simultaneous: a) 0 ms delay trials this was classified as the highest level of accuracy (accuracy = 6); b) 100 ms delay trials accuracy = 5; c) 200 ms delay trials accuracy = 4; d) 300 ms delay trials accuracy = 3; e) 400 ms delay trials accuracy = 2; f) 500 ms delay trials accuracy = 1. For trials where participants responded the lights and tones were *not* simultaneous, for: a) 0 ms delay trials this was classified as the lowest level of accuracy (accuracy = 1); b) 100 ms delay trials accuracy = 2; c) 200 ms delay trials accuracy = 3; d) 300 ms delay trials accuracy = 4; e) 400 ms delay trials accuracy = 5; f) 500 ms delay trials accuracy = 6. Mean accuracy on light-tone trials was 4.7 (*SD* = 0.3).

Meta-Awareness. Meta-awareness was measured using trials from the light-tone portion of the method of constant stimuli task. Meta-awareness is defined as the within-participant correlation between confidence ratings and accuracy of responses on light-tone trials. Scores (within-participant correlation coefficients) ranged from -1 to 1, with higher scores indicating greater accuracy-confidence correspondence, i.e., higher meta-awareness.

Heartbeat-Tone Trials

The second portion of the Method of Constant Stimuli task focused on the simultaneity of interoceptive sensations of heartbeats and auditory tone stimuli. Similar to light-tone trials, participants observed a series of five of their heart beats, with each R-wave followed by a tone. The lag between the R-wave and tone was the same within a trial but varied across trials. There were six different delay conditions: 0 ms, 100 ms, 200 ms, 300 ms, 400 ms, or 500 ms. Delays were pseudorandomly ordered across trials, with trial order counterbalanced across baseline and post-test. Participants completed 60 heartbeat-tone trials, split into two, 30 trial blocks with a break between blocks.

After each trial, participants were asked to report whether the tones occurred at the same time as their heartbeats (with 2 response options: a) yes, at the same time or b) no, not at the same time). Participants were then asked to rate their confidence in their response on a likert scale ranging from 1 = not at all confident to 4 = completely confident. Participants completed six practice trials to confirm they understood instructions before beginning the task.

Participants were instructed to tune into their heartbeats without taking their pulse. They were instructed to tune into the same location in their body to sense their heartbeat across the task. Participants were informed that within each trial of 5 tones, tones either would or would not coincide with their heartbeats, and across all trials the tones and their heartbeats would be at the same pace or rhythm so they must specifically tune into whether the tones and heartbeats occurred *at the same time*.

Interoceptive Accuracy. Interoceptive Accuracy reflects how consistently a participant reported the same delay (on heartbeat-tone trials) to be coincident with their heartbeats. Analyses will focus on a continuous measure of judgement precision -- the participant's interquartile range (IQR) of the distribution of percent of simultaneous responses for each delay condition (Brener & Ring, 2016). Lower IQRs indicate more consistent responses and thus higher accuracy. Analyses of Interoceptive Accuracy included Light-Tone Accuracy as a covariate, to adjust for variance associated with the cognitive load of the task. Analyses of Interoceptive Accuracy also included mean heart rate during the heartbeat-tone trials as a covariate, to adjust for variance associated with potential increased salience of heart beats due to delayed recovery from the stress task.

Accurate Perceivers. Accurate heartbeat perceivers were determined by a within-participant chi-square test of the 2 judgements (simultaneous or not simultaneous) x 6 delay conditions. Accurate perceivers were defined as those with a chi-square $p < .01$ (Brener, Liu, & Ring 1993; Brener, Ring, & Liu, 1994).

Interoceptive Insight. Interoceptive Insight was measured using trials from the heatbeat-tone portion of the method of constant stimuli task. Interoceptive Insight is defined as the within-participant correlation between confidence ratings and accurate responses on a trial-by-trial basis. Given individual differences in which delay is perceived as simultaneous with the heartbeat, there is no delay for heartbeat-tone trials that can be considered universally accurate. The accurate delay was thus determined on a participant-by-participant basis to be whichever delay the participant most often rated as simultaneous (i.e., delay with the highest percent of simultaneous responses out of their total number of simultaneous responses). Only $N = 66$ participants rated a single delay as more often simultaneous relative to all other delays (i.e., other participants had "ties" between multiple delays). Thus, Interoceptive Insight could only be computed for this subset of participants for whom we could determine their accurate delay, hereby called "favorite" delay to avoid confusion with trial accuracy.

Unlike with accuracy for light-tone trials, accuracy on heartbeat-tone trials for the calculation of Interoceptive Insight was a dichotomous variable: Trials where participants rated their favorite delay as simultaneous or where they rated a non-favorite delay as not-simultaneous were classified as accurate trials ("1"). Trials where participants rated their favorite delay as non-simultaneous or where they rated a non-favorite delay as simultaneous were classified as inaccurate trials ("0"). Scores (within-participant correlation coefficients) thus ranged from -1 to 1, with higher scores indicating greater accuracy-confidence correspondence, i.e., higher Interoceptive Insight.

Neutral Faces Task

Participants complete a neutral faces task designed to assess emotional spillover from the TSST onto neutral stimuli. They completed the neutral faces task twice (before the TSST and immediately after the TSST) during each of the 2 study visits (baseline and post-intervention), for a total of four times. The task involves viewing 60 faces with a neutral expression from the Chicago Face Database (Ma, Correll, & Wittenbrink, 2015; https://www.chicagofaces.org/). Four different sets of 60 faces were used for a different set each of the four times participants completed the task, to avoid familiarity effects. Sets of faces were matched on age, race, gender, and attractiveness, with the order counterbalanced across timepoints and pre/post TSST. Race distribution within each set was based on the 2018 U.S. census. Within a set, trials were pseudorandomly presented. Participants are introduced to the task with the following text:

"Every day we make quick judgments about people based on their face, appearance, gait (i.e., style of walking), style, and other visual characteristics. For example, we might use these quick judgments to help determine who we might approach to ask for directions or help, or who we should avoid.

Here we are asking you to make similar quick judgments about how much you like different people.

You will see a series of faces appear one at a time. Your task is to rate how much you like each person. Try not to overthink your answers; just give your honest gut response.

You will need to respond quickly, as the faces do not stay on the screen for very long."

Participants are asked to use the index finger of their dominant hand to respond. For each face, they response to the prompt "How much do you like this person?" using a 4-point rating scale ranging from 1, "Not at all" to 4, "Very much." They completed 4 practices trials to confirm understanding of the task. Each face appears with the rating scale beneath it. The screen advances to the next face when the participant rates that face, or after 3 seconds, whichever comes sooner. Thus if participants fail to respond within 3 seconds no response would be recorded for that face/trial.

Emotional Spillover. Emotional spillover is the difference in average face liking from post-TSST to pre-TSST. The pre-TSST average liking is meant to assess baseline liking of neutral faces, as there are likely individual differences in trait liking. We subtracted average liking post-TSST from average liking pre-TSST to evaluate the extent to which stress from the TSST influences liking of the neutral faces. Higher numbers thus indicate greater negatively-valenced emotional spillover.

Standardized Surveys

Multidimensional Assessment of Interoceptive Awareness (MAIA)

Interoceptive Sensibility was measured as the total score on the Multidimensional Assessment of Interoceptive Awareness Version 2 (MAIA-2; Mehling, Acree, Stewart, Silas, & Jones, 2018), which participants completed as part of the main questionnaire block at the beginning of the session. Scores range from 0 to 185. Higher scores indicate greater self-reported interoceptive abilities. Cronbach's alpha for the MAIA was .91.

Psychological Well-Being Scales (PWB)

Participants completed the 42-item version of Ryff's (1989) PWB scale. The scale consists of six subscales with 7 items each: autonomy, environmental mastery, personal growth, positive relations with others, purpose in life, and self-acceptance. Participants indicate on a 7-point Likert-type scale how true each statement is of themselves. Higher scores indicate greater well-being. Cronbach's alpha for the PWB was .92.

Center for Epidemiological Studies Depression Inventory (CES-D)

As part of the main questionnaire block at the beginning of the session, participants completed the CES-D (Radloff, 1977) a 20-item questionnaire assessing depression symptoms over the past week, rated on a 4-point scale (0 = rarely or none of the time, 1 = some or little of the time, 2 = moderately or much of the time, 3 = most or almost all the time). Scores on the

CES-D range from 0 to 60, with higher scores indicating more depressive symptoms. Cronbach's alpha for the CES-D was .89.

Spielberger Trait Anxiety Inventory Y2 (STAI)

As part of the main questionnaire block at the beginning of the session, participants completed the STAI (Spielberger, 1983), a 20-item questionnaire designed to assess trait anxiety. Participants rate items such as, "I worry too much over something that really doesn't matter," on a 4-point Likert-type scale (1 = almost never, 4 = almost always). Scores range from 20-80. Higher scores indicate greater trait anxiety. Cronbach's alpha for the STAI was .93.

COPE Inventory

As part of the main questionnaire block at the beginning of the session, participants completed a subset of scales from the COPE Inventory (Carver et al., 1989). Each scale consists of 4 items. Scores range from 4 to 16, with higher scores indicating more use of that style of coping. Only two of the scales were theoretically relevant for this project, both as measures of Acceptance of Subjective Experience: a) The Denial subscale measures participants' tendency to cope with stress by denying the reality of a stressor or avoiding beliefs that the stressor exists, and b) the Acceptance subscale measures participants' tendency to cope with stress by accepting the reality that has happened. Cronbach's alpha for COPE Denial was .62. Cronbach's alpha for COPE Acceptance was .73.

The other subscales administered were positive reinterpretation and growth (a tendency to identify positive aspects of stressors), behavioral disengagement (a tendency to give up on goals that the stressor is interfering with), and focus on and venting of emotion (a tendency to focus on distress and express those feelings). These last 3 subscales were not tested because they were not relevant to the hypotheses of this project.

Five Facet Mindfulness Questionnaire (FFMQ)

As part of the main questionnaire block at the beginning of the session, participants completed the FFMQ (Baer et al., 2008), a 39-item questionnaire assessing different facets of mindfulness. Cronbach's alpha for overall FFMQ was .89.

The sum of items on the Observing subscale will be analyzed as a measure of Awareness of Subjective Experience. Scores on this subscale range from 8-40. Higher scores indicate greater observing of experience. Cronbach's alpha for FFMQ Observing was .70.

The sum of items on the Non-Judging of Inner Experience subscale will be analyzed as a measure of Acceptance of Subjective Experience. Scores on this subscale range from 8-40. Higher scores indicate greater non-judging of inner experience. Cronbach's alpha for FFMQ Non-Judging of Inner Experience was .93.

Brief Experiential Avoidance Questionnaire (BEAQ)

As part of the main questionnaire block at the beginning of the session, participants completed the BEAQ (Gámez et al., 2014). The total (sum) score of the BEAQ will be analyzed as a measure of Acceptance of Subjective Experience. Scores range from 15 to 90. Higher scores indicate greater avoidance of experience. Cronbach's alpha for BEAQ was .82.

Emotional Styles Questionnaire (ESQ)

As part of the main questionnaire block at the beginning of the session, participants completed the ESQ (Kesebir, Gasiorowska, Goldman, Hirshberg, & Davidson, 2019). The total (sum) score on the Self-Awareness Subscale will be analyzed as a measure of Awareness of Subjective Experience. Scores on this subscale range from 4-28. Higher scores indicate greater self-awareness. Cronbach's alpha for ESQ Self-Awareness was .84.

Toronto Alexithymia Scale (TAS-20)

As part of the main questionnaire block at the beginning of the session, participants completed the TAS-20 (Bagby, Parker, & Taylor, 1994). The Difficulty Identifying Feelings subscale total (sum) score from the TAS-20 will be analyzed as a measure of Awareness of Subjective Experience. Scores range from 20-60. Greater scores indicate greater difficulty identifying feelings, an aspect of alexithymia. Cronbach's alpha for TAS Difficulty Identifying Feelings was .87.

Perceived Stress Scale (PSS-10)

As part of the main questionnaire block at the beginning of the session, participants completed the PSS-10 (Cohen, Kamarck, & Mermelstein,1983), a 10-item questionnaire designed to assess perceived stress in the past month. The total (sum) score will be used. Scores range from 0 to 40. Higher scores indicate higher perceived stress. Cronbach's alpha for the PSS-10 was .88.

Locus of Control (LOC)

As part of the main questionnaire block at the beginning of the session, participants completed the LOC (Levenson, 1973), a 24-item questionnaire designed to assess locus of control. The LOC includes 3 subscales: Internal Locus of Control, Powerful Others (fate is controlled by other people), and Chance (fate is controlled by chance). Scores range from 0-48 on each subscale. The Internal Locus of Control subscale total score will be analyzed. Cronbach's alpha for Internal Locus of Control was .48.

Dweck Mindset Instrument (DMI)

As part of the main questionnaire block at the beginning of the session, participants completed the DMI (Dweck et al., 1995), a 6-item questionnaire designed to assess incremental or malleable mindset compared to fixed or entity mindset. Scores range from 6 to 36. Lower scores indicate more fixed/entity views of intelligence and talent. Higher scores indicate more incremental/malleable views of intelligence and talent, or belief that intelligence and talent can be changed. Cronbach's alpha for Mindset was .88.

Cognitive Fusion Questionnaire (CFQ)

As part of the main questionnaire block at the beginning of the session, participants completed the CFQ (Gillanders et al., 2014), a 7-item questionnaire designed to assess cognitive fusion, or the degree to which thoughts are fused with reality/the degree of entanglement with thoughts and belief in them. Scores range from 7 to 49. Greater numbers reflect greater cognitive fusion. Cronbach's alpha for CFQ was .92.

Performance Appraisal Questionnaire (PAQ)

After the post-TSST Neutral Faces Task, participants completed the Performance Appraisal Questionnaire (Berry Mendes, Gray, Mendoza-Denton, Major, & Epel, 2007) regarding their performance during the TSST. The PAQ includes 4 items designed to assess demands, and 4 items designed to assess resources, (along with a question asking directly if participants felt threatened, and a question asking directly if they felt challenged). A Demands score and a Resources score were computed by summing relevant items. A Threat Ratio score was then computed by dividing the Demands score by the Resources score. Cronbach's alpha for PAQ Demands was .70, and for Resources was .68.

Positive and Negative Affect Schedules – Short Form, State (PANAS-NOW)

Participants completed the PANAS-NOW (Watson, Clark, & Tellegen, 1988), a measure of state positive and negative affect, immediately before and after the TSST procedure at each study visit. Items consist of 20 words that describe different feelings and emotions. Participants rate the extent to which they are feeling each of the words right now, on a scale of 1 = "Very slight or not at all," to 5 = "Extremely." The order of words was different each time participants completed the PANAS-NOW.

Free Response Questions

At the end of the post-test, before debriefing, participants were asked several free response questions, including "What is your definition of stress, particularly the definition of stress you were thinking of when completing the stress rating forms during the task?" and "What do you think our study is measuring?". These questions were preceded by the description "We'd like to ask you a few questions about your experience in the stress test today to help us improve our procedure. There are no right or wrong answers to these questions, we are simply trying to learn more about your experience." Questions were only asked at the end of post-test (and not at baseline) to not influence post-test coherence measures through reflection at baseline.

Statistical Analysis

Analyses were preregistered on the Open Science Framework (Sommerfeldt 2019, 2021a, 2021b). Analyses not included in preregistrations, or that were identified as exploratory in preregistrations, are described here as exploratory.

Coherence Focused Analyses

Following our previous data-analytic approach (Sommerfeldt et al., 2019), I estimated a series of linear mixed-effects models in which I regressed heart rate on subjective stress (centered around each participant's own mean), each measure of interest (mean centered; e.g., PWB), and their interaction (Brauer & Curtin, 2018). Each model thus included four fixed effects: subjective stress (Level 1), the well-being indicator of interest (Level 2), their interaction (Level 2), and the intercept. Each model also included a by-participant random intercept and a by-participant random slope for subjective stress. The two random effects were allowed to correlate. This model was represented in R as follows:

```
lmer(heartRate ~ stressClusterMeanCentered * measureofinterestCentered
        + (stressClusterMeanCentered|subject), data = dfLong)
```

My focus was on the stress by measure of interest interaction, which represents the degree to which within-participant associations between subjective stress and heart rate were moderated by the measure of interest. If this interaction was significant, I will say from now on that there is a relationship between subjective stress-heart rate coherence and the measure of interest. As subjective stress-heart rate coherence was not significantly associated with age, $b = -0.001$, $F(1, 117) = 0.23$, $p = .636$, nor gender b = -0.45, F(1, 104.5) = 0.61, p = .438 in the present sample, age and gender were not included as covariates.

I fit a separate model for each of the measures of interest. The Anova() function in the car package (v3.0.9; Fox & Weisberg, 2011) provided estimates of *F*, error *df* (via Kenward-Roger approximation), and *p*.

Mindfulness Intervention Focused Analyses

Analyses of impacts of the mindfulness intervention evaluated group by time interactions. For coherence, this substituted a group by time interaction as the measure of interested in the model described above.

Analyses of intervention effects on measures that were not coherence did not require the more complicated mixed effects models: I regressed the post-test score on group and the pre-test score, thus evaluating the effect of group on post-test score, adjusting for pre-test score. Group was coded with the control group = -0.5 and the mindfulness group = 0.5.

```
lm(postTest ~ group + preTest, data = dfWide)
```

Results

Conceptual Replication and Extension

Coherence and Well-Being

I predicted that higher subjective stress-heart rate coherence would be positively associated with psychological well-being, demonstrated through a positive association with PWB, and inverse associations with depressive symptoms measured through the Center for Epidemiological Studies Depression Inventory, and trait anxiety measured through the State-Trait Anxiety Inventory form Y2 (trait).

Subjective stress-heart rate coherence was not significantly related to PWB, $b = 0.000$, $F(1, 103.7) = 0.16$, $p = .691$, depressive symptoms, $b = -0.003$, $F(1, 97.6) = 1.03$, $p = .314$, nor trait anxiety, $b = -0.003$, $F(1, 99.7) = 1.46$, $p = .230$.

Table 1

Relationships Between Measures of Well-Being and Subjective Stress-Heart Rate Coherence

	***M* (*SD*)**	***b***	**SE**	***F***	**error *df***	***p***
PWB	223.1 (31.7)	0.000	0.001	0.16	103.7	.691
Depression	12.1 (8.8)	-0.003	0.003	1.03	97.6	.314
Anxiety	39.3 (11.1)	-0.003	0.002	1.46	99.7	.230

Coherence and Awareness

I predicted that higher subjective stress-heart rate coherence would be positively associated with awareness of mental states, demonstrated through positive associations with a) Meta-awareness measured through accuracy-confidence correspondence on a method of constant stimuli task, b) Observing measured through self-report on the Five-Facet Mindfulness Questionnaire, c) Self-Awareness measured through self-report on the Emotional Styles

Questionnaire, and through an inverse association with d) Difficulty Identifying Feelings measured through self-report on the Toronto Alexithymia Scale.

Subjective stress-heart rate coherence was not significantly associated with Meta-awareness, $b = 0.169$, $F(1, 91.0) = 1.61$, $p = .208$, FFMQ Observing, $b = 0.003$, $F(1, 105.0) = 0.26$, $p = 0.609$, ESQ Self-Awareness, $b = -0.003$, $F(1, 100.6) = 0.42$, $p = .512$, nor TAS-Difficulty Identifying Feelings, $b = -0.001$, $F(1, 107.8) = 0.05$, $p = .829$.

Table 2

Relationships Between Measures of Awareness and Subjective Stress-Heart Rate Coherence

	***M* (*SD*)**	***b***	**SE**	***F***	**error *df***	***p***
Metacognitive Insight	.40 (.23)	0.169	0.133	1.61	91.0	.208
Observing	26.2 (4.9)	0.003	0.005	0.26	105.0	.609
Identifying Feelings	14.5 (6.4)	-0.001	0.004	0.05	107.8	.829
Self-Awareness	18.6 (5.5)	-0.003	0.005	0.42	100.6	.517

Coherence and Acceptance

I predicted that higher subjective stress-heart rate coherence would be positively associated with acceptance of mental states, demonstrated through positive associations with a) Acceptance coping measured through self-report on the COPE and b) Non-judging of inner experience measured through self-report on the Five-Facet Mindfulness Questionnaire, and inverse associations with c) Denial coping measured through self-report on the COPE and d) Avoidance measured through self-report on the Brief Experiential Avoidance Questionnaire.

Subjective stress-heart rate coherence was not significantly associated with Acceptance coping, $b = 0.008$, $F(1, 95.2) = 0.71$, $p = .403$, FFMQ-Non-judging, $b = 0.004$, $F(1, 110.5) =$

1.85, *p* = .170, Denial coping, *b* = -0.032, *F*(1, 96.9) = 3.72, *p* = .057, nor Avoidance, *b* = -0.002, *F*(1, 97.6) = 0.66, *p* = .420.

Table 3

Relationships Between Measures of Acceptance and Subjective Stress-Heart Rate Coherence

	***M* (*SD*)**	***b***	**SE**	***F***	**error *df***	***p***
Non-Judging	28.0 (7.9)	0.004	0.003	1.85	110.5	.176
Acceptance	12.0 (2.6)	0.008	0.010	0.71	95.2	.403
Denial	5.0 (1.5)	-0.032	0.016	3.72	96.9	.057
Avoidance	43.0 (10.7)	-0.002	0.002	0.66	97.6	.420

Coherence and Interoception

I predicted subjective stress-heart rate coherence would be positively associated with interoceptive abilities, demonstrated through positive associations with a) interoceptive accuracy, b) interoceptive self-report (measured through self-report on the Multidimensional Assessment of Interoceptive Awareness), and c) interoceptive insight.

Subjective stress-heart rate coherence was not significantly associated with interoceptive accuracy, *b* = -0.000, *F*(1, 86.6) = 0.04, *p* = .849, interoceptive self-report, *b* = 0.001, *F*(1, 106.2) = 1.52, *p* = 0.221, nor interoceptive insight, *b* = -0.021, *F*(1, 48.6) = 0.01, *p* = .928.

Exploratory follow-up analyses examined relationships between Interoceptive Accuracy and a) Light-Tone Accuracy and b) heart rate during heartbeat-tone trials, by regressing Interoceptive Accuracy on each of these measures. Light-Tone accuracy was significantly associated with Interoceptive Accuracy, *b* = -41.18, *F*(1, 104) = 6.77, *p* = .011, such that higher accuracy on light-tone trials was associated with higher Interoceptive Accuracy (narrower IQR).

Mean heart rate during heartbeat-tone trials was not significantly associated with Interoceptive Accuracy, $b = 0.643$, $F(1, 101) = 2.22$, $p = .140$.

Only 13% ($N = 14$ of the $N = 106$ who completed the task) of participants with interoception task data passed the chi-square p <.01 criteria to be classified as accurate perceivers. An exploratory analysis examined whether accurate perceivers significantly differed in subjective stress-heart rate coherence relative to inaccurate perceivers, and there was no significant difference, $b = -0.01$, $F(1, 86.9) = 0.02$, $p = .897$.

Table 4

Relationships Between Measures of Interoception and Subjective Stress-Heart Rate Coherence

	***M* (*SD*)**	***b***	**SE**	***F***	**error *df***	***p***
Accuracy	270.5 (48.7)	-0.000	0.001	0.04	86.6	.849
Insight	-0.01 (.19)	-0.021	0.261	0.01	48.6	.928
Self-Reported (MAIA)	89.3 (24.9)	0.001	0.001	1.52	106.2	.221

Dimensions of Interoception

Exploratory analyses examined associations between the interoceptive dimensions of accuracy, self-report, and insight through Pearson's correlations. There were no significant associations between any of the dimensions of interoception, Table 5 details these results.

Table 5

Relations Across Dimensions of Interoception

	Accuracy	**Self-Report**	**Insight**
Accuracy	1.00	0.05	-0.21
Self-Report	0.05	1.00	0.10
Insight	-0.21	0.10	1.00

Note. Values represent correlations (*r*) between dimensions of interoception. See Table 4 for relations of each of these dimensions with subjective stress-heart rate coherence, which can be classified as a measure of interoceptive attribution.

Coherence and Emotional Spillover

I predicted subjective stress-heart rate coherence would be inversely associated with emotional spillover.

Subjective stress-heart rate coherence was not significantly associated with emotional spillover, $b = -0.100$, $F(1, 96.1) = 1.15$, $p = .286$.

Follow-up analyses demonstrated that change in negative affect (PANAS-NOW) was significantly associated with emotional spillover, b = 0.010, F(1, 116) = 5.73, p = 0.018, such that greater increases in negative affect from before to after the TSST were associated with greater decreases in liking ratings on the neutral faces task. Adjusting for change in negative affect in the model with coherence did not change the significance of those results. Change in positive affect was not significantly associated with emotional spillover, $b = -0.00$, $F(1, 116) = 2.03$, $p = .157$.

Coherence and Threat Ratio

Exploratory analyses examined whether subjective stress-heart rate coherence was associated with Threat Ratio.

Subjective stress-heart rate coherence was not significantly associated with Threat Ratio, $b = -0.037$, $F(1, 105.1) = 1.18$, $p = .281$.

Definitions of Stress

N = 75 participants provided responses to the question “What is your definition of stress, particularly the definition of stress you were thinking of when completing the stress rating forms during the task?” at post-intervention. Many participants (*N* = 30) referenced physical sensations or the body in their definition, for example “A sense of distress, anxiety, or nervousness in the body,” and “To my understanding, stress is the result of how our bodies respond to certain situations. For example, stressful situations will likely result in an increased heart rate, perspiration and anxiety.” Participants who mentioned physical manifestations had an average coherence BLUP at post-test (the same session where they answered this question) of 0.20 (identical to the mean of participants who did not mention the body), ranging from -0.190 to 0.986 (for participants who did not mention the body: -0.102 to 1.601). Half of the participants (*N* = 15) who included physical manifestations in their response specifically mentioned heart rate or heartbeats, e.g., “Rapid heart beat, nervousness, and not knowing how well I would perform.” This subset of participants who mentioned heart rate had an average coherence BLUP at post-test of 0.25, ranging from 0.002 to 0.604.

One participant (with post-test coherence of 0.483), specifically referenced attending to mental feelings and not the body, differentiating the two: “I was thinking about how I was mentally experiencing stress rather than how it was manifesting in my body.” Some participants acknowledged the connection between mental feelings and physiological responses: “Mental distress/fear involving increased heart rate and/or breathing,” and “Amount of physical change that is caused by mental and emotional change.” Several participants acknowledged stress as both mental and physical: “Stress is feeling anxious and includes the physical and mental aspects,” and “Stress is the amount of discomfort I felt psychologically and physically.”

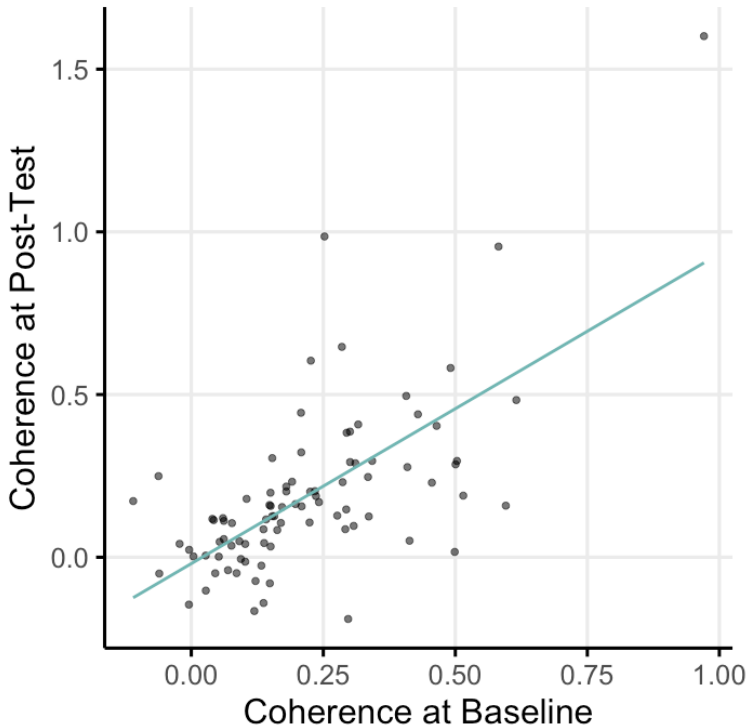
In their definitions of stress, participants repeatedly mentioned "tension" (*N* = 6), "pressure" (*N* = 4), "anxiety" (*N* = 26), and "nervousness" (*N* = 16). Tension without other mentions of physical sensations was not assumed to include the body for the earlier classification, as it seemed possible that participants could mean mental tension.

Test-Retest Reliability

As the method of measuring coherence was novel, in exploratory analyses I examined test-retest reliability of coherence across the two timepoints that were separated by 4 weeks. For each timepoint, Best Linear Unbiased Predictors (BLUPs) were extracted from a mixed effects model regressing heart rate on subjective stress with a random effect for stress. For the entire sample, the correlation between the baseline and post-test BLUP was *ICC(1,1)* = .62, (*r* = .66). Since I expected coherence for the mindfulness group to change (specifically, to improve), I also examined this correlation within each group separately. For the control group, *ICC(1,1)* = .63, (*r* = .69), whereas for the mindfulness group, *ICC(1,1)* = .62, (*r* = .61). Figure 5 depicts the relationship between coherence at Baseline compared to Post-Test.

Figure 5

Test-Retest Reliability of Coherence



Mindfulness Intervention

Participants in the mindfulness group did not significantly differ from controls in age, gender, or racial identity. Table 7 details demographics by group.

Table 7

Group Demographics

	Control	**Mindfulness**
***N* post-test** / *N* baseline	**51** / 63	**43** / 57
Return%	81%	75%
Age *M* (*SD*)	34.6 (12.74)	34.7 (13.8)
Gender	35 Women 15 Men	30 Women 4 Nonbinary people 9 Men
Racial identity	78% white	74% white

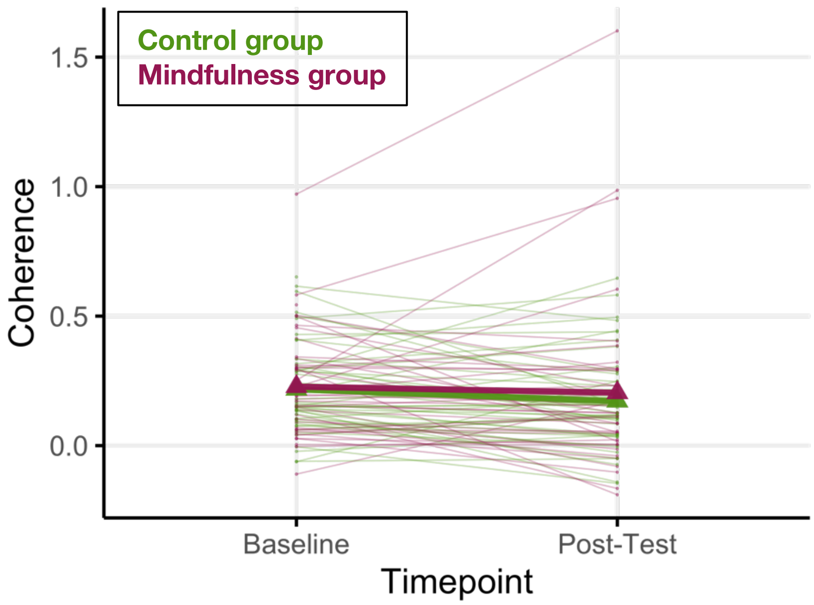
Mindfulness and Coherence

I predicted that from baseline to post-test, participants in the mindfulness training group would demonstrate greater increases than the control group in subjective stress-heart rate coherence.

Mindfulness training was not significantly associated with greater increases in subjective stress-heart rate coherence, $b = 0.012$, $F(1, 46.0) = 0.11$, $p = .740$.

Figure 6

Change in Coherence from Baseline to Post-Test by Group



Mindfulness and Awareness

I predicted that from baseline to post-test, participants in the mindfulness training group would demonstrate greater increases than the control group in awareness of subjective states; demonstrated through increases in a) Meta-Awareness measured through accuracy-confidence correspondence on a Method of Constant Stimuli task, b) Observing measured through self-report on the Five-Facet Mindfulness Questionnaire, c) Self-Awareness measured through self-report on the Emotional Styles Questionnaire, and decreases in d) Difficulty Identifying Feelings measured through self-report on the Toronto Alexithymia Scale.

Mindfulness training was not significantly associated with changes in Meta-Awareness, $b = -0.019$, $F(1, 59) = 0.22$, $p = .638$, FFMQ-Observing, $b = 1.29$, $F(1, 91) = 3.29$, $p = .073$, Difficulty Identifying Feelings, $b = -0.334$, $F(1, 91) = 0.21$, $p = .648$, nor ESQ-Self-Awareness, $b = 1.039$, $F(1, 84) = 2.05$, $p = .156$.

Table 8

Intervention Effects on Awareness

	M (*SD*) Change						
	Control	**Mindfulness**	***b***	**SE**	***F***	**error *df***	***p***
Metacognitive Insight	0.04 (0.24)	0.02 (0.18)	-0.019	0.04	0.22	59	.638
Observing	0.04 (3.09)	1.14 (4.09)	1.290	0.78	3.29	91	.073
Identifying Feelings	0.31 (4.37)	0.16 (2.79)	-0.334	0.73	0.21	91	.648
Self-Awareness	-0.77 (4.28)	0.23 (2.99)	1.039	0.73	2.05	84	.156

Note. Means and standard deviations represent change, with pre-test subtracted from post-test.

Mindfulness and Acceptance

I predicted that from baseline to post-test, participants in the mindfulness training group would demonstrate greater increases than the control group in acceptance of subjective states; demonstrated through increases in a) Acceptance coping measured through self-report on the COPE and b) Non-judging of inner experience measured through self-report on the Five-Facet Mindfulness Questionnaire, and inverse associations with c) Denial coping measured through self-report on the COPE and d) Avoidance measured through self-report on the Brief Experiential Avoidance Questionnaire.

Mindfulness training was not significantly associated with changes in Acceptance coping, $b = 0.275$, $F(1, 86) = 0.41$, $p = .526$, Denial coping, $b = 0.090$, $F(1, 86) = 0.09$, $p = .765$, nor Avoidance, $b = -1.016$, $F(1, 85) = .465$, $p = .497$. Mindfulness training was significantly associated with changes in Non-judging, $b = 2.197$, $F(1, 91) = 4.83$, $p = .030$, such that participants in the mindfulness training group demonstrated significantly greater increases in Non-judging relative to participants in the control group.

Table 9

Intervention Effects on Acceptance

	M (*SD*) Change						
	Control	**Mindfulness**	***b***	**SE**	***F***	**error *df***	***p***
Non-Judging	-0.49 (4.04)	1.79 (6.10)	2.200	1.00	4.83	91	.030*
Acceptance	0.08 (2.48)	0.17 (2.05)	0.275	0.43	0.41	86	.526
Denial	-0.13 (1.47)	-0.10 (1.51)	0.090	0.30	0.09	86	.765
Avoidance	-1.04 (6.23)	-1.98 (7.63)	-1.016	1.49	0.47	85	.497

Note. Means and standard deviations represent change, with pre-test subtracted from post-test.

Beliefs About the Study

N = 88 participants provided responses to the question "What do you think our study is measuring?" at the end of the post-test visit. Some participants evidenced prior knowledge of the Center for Healthy Minds and our reputation for being involved with mindfulness research, which likely interfered with study blinding attempts, "I'm guessing you're studying mindfulness since you are the institute for healthy minds." However, a fair number of participants (*N* = 7) demonstrated through their responses to this question that they were convinced by the active control, "How people who spend a lot of time on their phones manage stress, how being on your phone more makes you feel more disconnected to your body," "Cell phone usage effect on stress level," "Effects of screen time on mental well-being." A couple participants (*N* = 2) were able to identify the primary measure (subjective experience-physiology coherence), e.g., "The correlation/relationship between our physiologic and emotional responses to different situations." Some participants also identified other key measures of the study, such as emotional spillover (*N* = 3), e.g., "Perhaps how stressful situations affect our response to others (i.e. the judging of faces before and after the stress test)." Six participants noted the study was examining the ability to “control” stress, their emotions, or their body responses to stress, through comments such as “… this study seemed to test one's ability to control their thoughts and emotions during potentially stressful situations,” “Determining if a four week intervention changes subjects ability to identify/control stress,” and “..to control and be in tune with emotions and feeling.” Interestingly, controlling and being aware of feelings were potentially confounded in the last two examples.

Discussion

This project sought to better understand subjective stress-heart rate coherence by examining its relations to interoceptive abilities across a range of dimensions, awareness of inner states, acceptance of inner states, emotional spillover, and well-being. Furthermore, I evaluated whether subjective stress-heart rate coherence could be trained through mindfulness, which is thought to increase awareness and acceptance of our inner states. Based on past work (Sommerfeldt et al., 2019; Sommerfeldt et al., in prep), I expected these effects to be small. Due to pandemic impacts, the study was not sufficiently powered to detect small effects, and accordingly, few significant associations were found in support of hypotheses. The one exception was participants in the mindfulness intervention demonstrated significantly greater increases in non-judgement of inner experience from baseline to post-test relative to participants in the control condition. This project also developed a novel procedure specifically designed to assess subjective stress-physiology coherence, and coherence assessed through this procedure was moderately reliable. This study also provides information on lay definitions of stress that participants were using when reporting on their subjective experience, as well as whether these reflections included the body.

Conceptual Replication: Coherence and Well-Being

Surprisingly, I did not find stronger subjective stress-heart rate coherence to be tied to higher psychological well-being, lower depression, and lower anxiety, as I found previously in two large samples (Sommerfeldt et al., 2019; Sommerfeldt et al., in prep). Similarly, as discussed in the introduction, Brown et al. (2019), despite using a different procedure and investigating the subjective experience of valence, also found similar associations with stronger valence-heart rate coherence being tied to higher subjective well-being, lower depression, and lower anxiety. The sample size here was nearly 1/10th the size of that in Sommerfeldt et al. (2019), resulting in drastically reduced power to detect effects. The stress induction procedure used to measure coherence in this study was also different from that used in previous studies, so the lack of replication could be due to the measurement procedure.

Extension to Awareness and Acceptance

There were no significant associations between subjective stress-heart rate coherence and measures of awareness or acceptance. While not significant, associations with the 8 measures of awareness and acceptance were in the expected directions. These analyses were meant to establish a nomological network supporting subjective experience-physiology coherence as a measure of awareness and acceptance of subjective states. I was particularly surprised that coherence was not significantly associated with difficulty identifying feelings, due to my conceptualization of coherence as a behavioral measure inverse to alexithymia. However, Muhtadie (2017) also did not find a significant association between subjective experience-physiology coherence and the Difficulty Identifying Feelings subscale of the TAS. Relatedly, a recent meta-analysis found no association between objectively measured interoceptive accuracy and alexithymia (Trevisan et al., 2019). Lack of significant associations do not prove the null hypotheses, however it is possible that subjective experience-physiology coherence is not assessing awareness and acceptance of subjective states. Afterall, physiology does not represent an objective measure of subjective states, so the association between physiology and subjective experience is not an objective measure of accuracy of perceiving subjective states.

Definitions of Stress

Forty percent of participants included physical manifestations of stress in their definitions of stress. Before the stress test, participants were outfitted with physiological recording equipment, including a belt across their waist which held a mobile transmitter, 3 sensors across their torso, wires clipped to the sensors that then plugged into the transmitter at their waist, a tight elastic belt to measure respiration through tension changes, with the tension belt also wired into the transmitter at their waist, plus 2 sensors on their non-dominant palm to measure changes in moisture in their skin, where were connected via 2 wires to a transmitter worn as a bracelet on their wrist. This equipment setup typically took 8-15 minutes, and the equipment remained on through the stress test. Participants were told the purpose of each device during setup. These details are provided to emphasize that the physiological equipment was extensive. Participants may have been primed by the physiological recording equipment to be thinking about physical manifestations of stress during the TSST, which reflected in the definitions of stress provided by many participants. However, we specifically designed the study so that the interoception task occurred after the stress test in order to avoid priming participants through having them focus on their heart before the measurement of coherence, with the idea that the interoception task may prime more focus on the heart and potentially bias coherence ratings from participants' usual trait coherence. Conversely, it was not possible to setup physiological equipment without participants being aware of it.

Interoception

There are numerous challenges to the measurement of interoceptive accuracy. The task used here was selected based on advantages over heartbeat counting and two-alternative forced choice discrimination tasks (Brener & Ring, 2016), despite added implementation complexities. However, the method of constant stimuli task used here does involve significant cognitive load. Participants must keep track of series of stimuli perceived through different sensory processing pathways.

Many interoception tasks demonstrate floor effects – for example, only around 40% of people are accurate heartbeat perceivers (Brener, Ring, & Liu, 1994). In the present study, only 13% (*N* = 14) participants met the threshold for accurate perceivers. This discrepancy may be due to the difference in the number of trials used compared to other studies. Brener, Ring, and Liu (1994) used 120 heartbeat-tone trials, whereas the current study used only 60 heartbeat-tone trials. Given the 6 different delay conditions, there were only 10 trials per delay in the present study. While Kleckner et al. (2015) found 40-60 trials was sufficient for reliability and power, differences across tasks will impact the optimal number of trials. Notably, the task used by Kleckner et al. (2015) only included 2 delay conditions. The current task took about 25-35 minutes to complete, with variation due to response time and heart rate (faster heart rates led to faster stimuli presentations). The number of trials and coincident task length present a considerable burden to participants.

Relative to the number of accurate perceivers (*N* = 14), more participants (*N* = 66) were able to identify one delay as more often simultaneous with their heartbeats relative to all other delays (just not significantly more than chance). Still, failure to identify a single delay more often than others (even with this more relaxed threshold) prevented calculation of insight scores for *N* = 40 participants. Individual differences in which delay is perceived as simultaneous with the heartbeat means there is no universal correct delay that applies across individuals to examine in relation to confidence ratings.

As mentioned above, the interoception task occurred after the stress test. Thus, heart rate during the interoception task was likely still elevated from the stress test for some participants more than others, as individual differences in latency to recover from stress have been observed (Papousek et al., 2017). There was approximately a 5-10 minute delay between the stress test and the interoception task. Following the stress test, most of the physiological recording equipment was removed (all but the 3 sensors across the torso, which were connected to a different, wired Biopac system for the interoception task). Immediately after equipment removal, participants completed the Neutral Faces task, and then the Performance Appraisal Questionnaire. Elevated heart rate during the interoception task, associated with poorer recovery from the stressor, may have impacted task performance through increased salience of heart signals. This confound of poorer recovery with increased heart rate during the interoception task was a compromise to prioritize the validity of the coherence measure, the primary measure of the study. Analyses of interoceptive accuracy included average heart rate during the interoception task as a covariate in attempt to mitigate this concern.

This study was inconclusive whether interoceptive accuracy is associated with subjective experience-physiology coherence due to limited power to detect small effects. Lack of significant associations between subjective stress-heart rate coherence and interoceptive abilities is not entirely unexpected. As discussed earlier, it is possible that individuals attend to more mental aspects of subjective experiences without explicit attention to physiological signals.

Alternatively, strong coherence may require the ability to accurately perceive physiological signals and this conscious awareness of the physiology supports awareness of subjective states in a way that tracks strongly with the physiology. From this foundation of accurate awareness of physiological signals, individuals with strong coherence appraise and interpret what those physiological signals mean in relation to their subjective state thus supporting the correlation between physiology and subjective experience. Future studies should evaluate interoceptive accuracy and subjective experience-physiology coherence in larger samples to better evaluate this relationship.

It should be noted that even if a correlation is shown between interoceptive accuracy and strong coherence, it is still not necessarily the case that individuals are aware of the connections between physiology and subjective feelings. We can differentiate between having accurate perceptions of physiological signals, and having awareness of the connections between physiology and subjective experience. For example, an individual may be able to separately, precisely, perceive both their physiological signals and their subjective experience, but are not consciously mapping one to the other. They may simply feel their heart beating faster, and feel their mental state of stress, and be able to report on each of these states separately in a way that shows strong coherence between the two, although they are not consciously deducing from their awareness of their physiological state -- so I must be stressed. It is a matter of whether these are perceived as separate phenomena: I can feel my heart beating and I can perceive that I feel stressed (aware of each separately) – versus -- I can feel my heart beating and so I must feel stressed (with awareness of the connection between the two). Demonstrating that interoceptive accuracy and strong coherence are associated does not necessarily imply that the individual is consciously interpreting or appraising what their physiology means for their mental state, or that they are aware that their physiology and subjective feelings are connected. Thus, future studies should also assess individuals' beliefs about their interoceptive signals, particularly what these signals mean in terms of subjective experiences.

Future studies should also examine whether awareness of other interoceptive signals, such as gastric or respiratory, supports subjective experience-physiology coherence. It may be that interoceptive accuracy varies across different bodily systems, with some individuals more tuned into one bodily axis over others. Even if they are not accurate perceivers of their heart, if they are accurate perceivers of another bodily system, this could support subjective experience-physiology coherence.

Emotional Spillover

The emotional spillover task used here employs a more intense subjective experience induction relative to brief presentations of emotional images, so may be more sensitive to detecting emotional spillover. Unexpectedly, a fair number of participants demonstrated *increases* in liking of neutral faces following the stress test. As mentioned earlier, stress can vary in valence. If participants felt challenged, rather than threatened by the stress test, the stress test may have induced a more positively valenced form of stress. Alternatively, participants may also have felt a negatively valenced form of stress during the stress test, but experienced an increase in positive affect upon its conclusion, for example relief that the test was over. The inclusion of the PANAS before and after the stress test allowed for examining changes in positive and negative affect from before to after the stress test, corresponding well with the emotional spillover task, which was also completed on either side of the stress test. Analyses of relations between change in negative and positive affect relative to change in liking of the faces revealed a significant association between increases in negative affect and decreases in liking ratings of the faces, i.e., greater degree of negative emotional spillover.

While outside the scope of the current project, future work should examine whether emotional spillover impacts perceptions of some people more than others. It is possible that there is an interaction between emotional spillover and implicit bias, whereby individuals with certain perceived identities are more likely to be attributed negative bias from emotional spillover compared to others.

Test-Retest Reliability

Intraclass correlations between subjective stress-heart rate coherence assessed 4 weeks apart were moderate, with an ICC of .62, which falls into the moderate reliability range. Muhtadie (2017) also examined test-retest reliability of subjective experience-physiology coherence, but across a 1-week period. Muhtadie (2017) examined subjective experiences of valence and arousal in relation to physiological indices of heart period and somatic activity (measured via a pressure sensor under the participants' chair) using within-person lagged cross-correlations as the coherence measure. Arousal-somatic activity coherence calculated using the absolute value (ignoring the direction of the coherence correlation) had the strongest test-retest reliability at r = .51, followed by valence-heart period coherence calculated using signed maximum with test-retest r = .47, and arousal-heart period coherence calculated using signed maximum with test-retest r = .33. The present study showed higher test-retest reliability despite the longer timescale between test and retest (4 weeks). The increase test-retest reliability could be due to examining subjective experience of stress rather than valence or arousal, given the benefits discussed earlier. Additionally, rather than within-person correlations as the coherence measure, I used what are effectively within-participant slopes, the BLUPs extracted from the mixed effects model, which might be more reliable compared to within-person correlations.

While the correlation between coherence measures across timepoints in the current study was moderate (*r* = .61-.69), examining the distribution of coherence scores across timepoints reveals that there were more negative coherence scores at post-test. It is possible that this is due to habituation of either subjective or cardiac responses to the TSST. Despite counterbalancing two different speech and math tasks, the overall procedure was still largely similar, and the uncertainty and novelty of the TSST play a key role in the stressfulness of the procedure (Labuschagne et al., 2019).

Mindfulness Intervention

The one significant finding was that the mindfulness group demonstrated greater increases in Non-judging relative to the control group. While it is encouraging that the mindfulness group demonstrated increases in Non-judging, this finding should be taken with the caveat that the language of FFMQ includes jargon of mindfulness-based interventions. Previous work has highlighted that participation in mindfulness interventions is likely to familiarize participants to this jargon and way of conceptualizing behavior and the mind, which may have primed participants to respond differently on that questionnaire (Lutz et al., 2019; Van Dam, Hobkirk. Danoff-Burb, & Earleywine, 2012).

As hypothesized here, mindfulness is thought to cultivate greater acceptance and self-awareness of internal states. As self-reports depend on self-awareness and acceptance for validity, this potentially presents a confound whereby participants are more accurate self-reporters following intervention compared to their reports at baseline. This has the potential to mitigate the power to detect effects, if the precision of reporting is changing in tandem with any actual changes in behavior or mental processes.

The psychoeducation aspect of the intervention also may have primed expectancy effects by discussing scientific evidence showing benefits of mindfulness practice. We attempted to minimize expectancy effects by having the control group record their screen time, with the idea that by monitoring screen time it may decrease, which could potentially increase well-being. Analysis of participants' responses to what they thought the study was about did show that several people believed this red herring: that we were examining the relationship between screen time and well-being. Yet while these free response answers to the probe about what the study was about demonstrated that the active control helped manage expectancy effects surrounding improved well-being, ability to manage stress, and connection with the body, it was not convincing for all participants. (Note that this question was broad and not specific to the intervention. It is possible that additional participants were convinced by the screen time sham and this question simply did not elicit responses that evidenced this). Even for those who did buy into the active control cover story, it is unlikely their expectancies were as strong as those established by the mindfulness intervention. Thus, it is possible that participants' performance on study measures at post-test were impacted by motivation from these expectations and beliefs from their group condition.

Conclusions

To establish whether body awareness supports subjective experience-physiology coherence, it will also be important to examine whether training interoceptive accuracy without training awareness or acceptance of mental states, results in increases in subjective experience-physiology coherence. Expanding on this, future work should also explore whether training of interoceptive awareness augmented by training that seeks to tune the appraisal of interoceptive signals provides greater benefits to mental health relative to training interoceptive awareness alone.

While limited by sample size, this study developed two novel measurements and an experimental design that can be used by other studies in the future. Future studies should seek to increase the reliability of the coherence measurement, perhaps by exploring whether reliability of the coherence measurement relates to habituation to the stress induction procedure and ways to maintain similar stressfulness across repeated assessments. It is also important to keep in mind that failing to find significant effects is not the same as proving there is no effect. Future studies with larger samples will provide more certainty around the associations explored here and outlined in the overarching framework (Figure 2). These data will also be shared publicly so that other researchers can explore additional questions through the wealth of measures collected.

References

Al, E., Iliopoulos, F., Forschack, N., Nierhaus, T., Grund, M., Motyka, P., ... & Villringer, A. (2020). Heart–brain interactions shape somatosensory perception and evoked potentials. *Proceedings of the National Academy of Sciences*, *117*(19), 10575-10584.

Allen, J. J., Chambers, A. S., & Towers, D. N. (2007). The many metrics of cardiac chronotropy: A pragmatic primer and a brief comparison of metrics. *Biological Psychology*, *74*(2), 243-262.

Alvear, D., Soler, J., & Cebolla, A. (2022). Meditators' Non-academic Definition of Mindfulness. *Mindfulness*, 1-11.

Andrews, J., Ali, N., & Pruessner, J. C. (2013). Reflections on the interaction of psychogenic stress systems in humans: The stress coherence/compensation model. *Psychoneuroendocrinology*, *38*(7), 947–961. https://doi.org/10.1016/j.psyneuen.2013.02.010

Baer, R. A., Smith, G. T., Lykins, E., Button, D., Krietemeyer, J., Sauer, S., ... & Williams, J. M. G. (2008). Construct validity of the five facet mindfulness questionnaire in meditating and nonmeditating samples. *Assessment*, *15*(3), 329-342.

Bagby, R. M., Parker, J. D., & Taylor, G. J. (1994). The twenty-item Toronto Alexithymia Scale—I. Item selection and cross-validation of the factor structure. *Journal of Psychosomatic Research*, *38*(1), 23-32.

Beck, A. T. (2002). Cognitive models of depression. *Clinical Advances in Cognitive Psychotherapy: Theory and Application*, *14*(1), 29-61.

Beck, A. T., Steer, R. A., & Brown, G. (1996). Beck depression inventory–II. *Psychological Assessment*.

Benedek, M. & Kaernbach, C. (2010). A continuous measure of phasic electrodermal activity. *Journal of Neuroscience Methods*, 190, 80-91.

Berry Mendes, W., Gray, H. M., Mendoza-Denton, R., Major, B., & Epel, E. S. (2007). Why egalitarianism might be good for your health: Physiological thriving during stressful intergroup encounters. *Psychological Science, 18*(11), 991-998.

Bishop, S. R., Lau, M., Shapiro, S., Carlson, L., Anderson, N. D., Carmody, J., ... & Devins, G. (2004). Mindfulness: A proposed operational definition. *Clinical Psychology: Science and Practice*, *11*(3), 230.

Bornemann, B., & Singer, T. (2017). Taking time to feel our body: Steady increases in heartbeat perception accuracy and decreases in alexithymia over 9 months of contemplative mental training. *Psychophysiology*, *54*(3), 469-482.

Brauer, M., & Curtin, J. J. (2018). Linear mixed-effects models and the analysis of nonindependent data: A unified framework to analyze categorical and continuous independent variables that vary within-subjects and/or within-items. *Psychological Methods*, *23*(3), 389.

Brener, J., Liu, X., & Ring, C. (1993). A method of constant stimuli for examining heartbeat detection: Comparison with the Brener-Kluvitse and Whitehead methods. *Psychophysiology*, *30*(6), 657-665.

Brener, J., & Kluvitse, C. (1988). Heartbeat detection: judgments of the simultaneity of external stimuli and heartbeats. *Psychophysiology*, *25*(5), 554-561.

Brener, J., Ring, C., & Liu, X. (1994). Effects of data limitations on heartbeat detection in the method of constant stimuli. *Psychophysiology*, *31*(3), 309-312.

Brener, J., & Ring, C. (2016). Towards a psychophysics of interoceptive processes: the measurement of heartbeat detection. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *371*(20160015), 1-9. http://dx.doi.org/10.1098/rstb.2016.0015

Brown, C. L., Van Doren, N., Ford, B. Q., Mauss, I. B., Sze, J. W., & Levenson, R. W. (2020). Coherence between subjective experience and physiology in emotion: Individual differences and implications for well-being. *Emotion, 20*(5), 818–829. https://doi.org/10.1037/emo0000579

Carver, C. S., Scheier, M. F., & Weintraub, J. K. (1989). Assessing coping strategies: a theoretically based approach. *Journal of Personality and Social Psychology*, *56*(2), 267.

Cohen, S., Kamarck, T., & Mermelstein, R. (1983). A global measure of perceived stress. *Journal of Health and Social Behavior*, 24, 385-396. http://dx.doi.org/10.2307/2136404

Dahl, C. J., Wilson-Mendenhall, C. D., & Davidson, R. J. (2020). The plasticity of well-being: A training-based framework for the cultivation of human flourishing. *Proceedings of the National Academy of Sciences*, *117*(51), 32197-32206.

Diener, E. D., Emmons, R. A., Larsen, R. J., & Griffin, S. (1985). The satisfaction with life scale. *Journal of Personality Assessment*, *49*(1), 71-75.

Domschke, K., Stevens, S., Pfleiderer, B., & Gerlach, A. L. (2010). Interoceptive sensitivity in anxiety and anxiety disorders: an overview and integration of neurobiological findings. *Clinical Psychology Review*, *30*(1), 1-11.

Duchesne, A., & Pruessner, J. C. (2013). Association between subjective and cortisol stress response depends on the menstrual cycle phase. *Psychoneuroendocrinology*, *38*(12), 3155-3159.

Dunne, J. D. (2015). Buddhist styles of mindfulness: A heuristic approach. In *Handbook of Mindfulness and Self-Regulation* (pp. 251-270). Springer, New York, NY.

Dweck, C. S., Chiu, C. Y., & Hong, Y. Y. (1995). Implicit theories and their role in judgments and reactions: A word from two perspectives. *Psychological Inquiry, 6*(4), 267-285.

Erle, T. M., Mitschke, V., & Schultchen, D. (2021). Did my heart just leap or sink? The role of personality for the relation between cardiac interoception and well-being. *Personality and Individual Differences*, *170*, 110493. https://doi.org/10.1016/j.paid.2020.110493

Feldman-Barrett, L. (2017). The theory of constructed emotion: an active inference account of interoception and categorization. *Social Cognitive and Affective Neuroscience*, *12*(1), 1-23.

Fox, J., & Weisberg, S. (2011). Multivariate linear models in R. *An R Companion to Applied Regression*. *Los Angeles: Thousand Oaks*.

Fu, Q., Fu, X., & Dienes, Z. (2008). Implicit sequence learning and conscious awareness. *Consciousness and Cognition*, *17*(1), 185-202.

Gámez, W., Chmielewski, M., Kotov, R., Ruggero, C., Suzuki, N., & Watson, D. (2014). The brief experiential avoidance questionnaire: development and initial validation. *Psychological Assessment*, *26*(1), 35.

Garfinkel, S. N., Seth, A. K., Barrett, A. B., Suzuki, K., & Critchley, H. D. (2015). Knowing your own heart: Distinguishing interoceptive accuracy from interoceptive awareness. *Biological Psychology*, *104*, 65–74. https://doi.org/10.1016/j.biopsycho.2014.11.004

Gillanders, D. T., Bolderston, H., Bond, F. W., Dempster, M., Flaxman, P. E., Campbell, L., ... & Masley, S. (2014). The development and initial validation of the Cognitive Fusion Questionnaire. *Behavior Therapy, 45*(1), 83-101. Retrieved from http://www.sciencedirect.com/science/article/pii/S0005789413000716

Goldberg, S. B., Imhoff-Smith, T., Bolt, D. M., Wilson-Mendenhall, C. D., Dahl, C. J., Davidson, R. J., & Rosenkranz, M. A. (2020). Testing the efficacy of a multicomponent, self-guided, smartphone-based meditation app: Three-armed randomized controlled trial. *JMIR mental health*, *7*(11), e23825.

Harrison, N. A., Gray, M. A., Gianaros, P. J., & Critchley, H. D. (2010). The Embodiment of Emotional Feelings in the Brain. *Journal of Neuroscience*, *30*(38), 12878–12884. https://doi.org/10.1523/JNEUROSCI.1725-10.2010

Hertel, P. T., & Mathews, A. (2011). Cognitive bias modification: Past perspectives, current findings, and future applications. *Perspectives on Psychological Science*, 6(6), 521-536.

Hofmann, S. G., Heering, S., Sawyer, A. T., & Asnaani, A. (2009). How to handle anxiety: The effects of reappraisal, acceptance, and suppression strategies on anxious arousal. *Behaviour Research and Therapy*, *47*(5), 389-394.

James, W. (1894). The Physical Basis of Emotion.pdf. *Psychological Review*, *1*, 516–529.

Kabat-Zinn, J. (1994). Wherever you go, there you are: Mindfulness meditation in everyday life. New York: Hyperion.

Kesebir, P., Gasiorowska, A., Goldman, R., Hirshberg, M. J., & Davidson, R. J. (2019). Emotional Style Questionnaire: A multidimensional measure of healthy emotionality. *Psychological Assessment*, *31*(10), 1234-1246.

Khalsa, S. S., Adolphs, R., Cameron, O. G., Critchley, H. D., Davenport, P. W., Feinstein, J. S., Feusner, J. D., Garfinkel, S. N., Lane, R. D., Mehling, W. E., Meuret, A. E., Nemeroff, C. B., Oppenheimer, S., Petzschner, F. H., Pollatos, O., Rhudy, J. L., Schramm, L. P., Simmons, W. K., Stein, M. B., … Zucker, N. (2018). Interoception and Mental Health: A

Roadmap. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *3*(6), 501–513. https://doi.org/10.1016/j.bpsc.2017.12.004

Killingsworth, M. A., & Gilbert, D. T. (2010). A wandering mind is an unhappy mind. *Science*, *330*, 932-932.

Kirschbaum, C., Pirke, K. M., & Hellhammer, D. H. (1993). The 'Trier Social Stress Test'–a tool for investigating psychobiological stress responses in a laboratory setting. *Neuropsychobiology*, *28*(1-2), 76-81.

Kleckner, I. R., Wormwood, J. B., Simmons, W. K., Barrett, L. F., & Quigley, K. S. (2015). Methodological recommendations for a heartbeat detection-based measure of interoceptive sensitivity. *Psychophysiology*, *52*(11), 1432-1440.

Kroenke, K., Spitzer, R. L., & Williams, J. B. (2001). The PHQ-9: validity of a brief depression severity measure. *Journal of General Internal Medicine*, *16*(9), 606-613.

Labuschagne, I., Grace, C., Rendell, P., Terrett, G., & Heinrichs, M. (2019). An introductory guide to conducting the Trier Social Stress Test. *Neuroscience & Biobehavioral Reviews*, *107*, 686-695.

Lapate, R. C., Rokers, B., Li, T., & Davidson, R. J. (2014). Nonconscious emotional activation colors first impressions: A regulatory role for conscious awareness. *Psychological Science*, *25*(2), 349-357.

Leganes-Fonteneau, M., Scott, R., & Duka, T. (2018). Attentional responses to stimuli associated with a reward can occur in the absence of knowledge of their predictive values. *Behavioural Brain Research*, *341*, 26-36.

Levenson, H. (1973). Multidimensional locus of control in psychiatric patients. *Journal of Consulting and Clinical Psychology*, 41(3), 397.

Lindquist, K. A., Satpute, A. B., & Gendron, M. (2015). Does Language Do More Than Communicate Emotion? *Current Directions in Psychological Science*, *24*(2), 99–108. https://doi.org/10.1177/0963721414553440

Lutz, A., Jha, A. P., Dunne, J. D., & Saron, C. D. (2015). Investigating the phenomenological matrix of mindfulness-related practices from a neurocognitive perspective. *American Psychologist*, *70*(7), 632–658. https://doi.org/10.1037/a0039585

Ma, D. S., Correll, J., & Wittenbrink, B. (2015). The Chicago face database: A free stimulus set of faces and norming data. *Behavior Research Methods*, *47*(4), 1122-1135.

Mehling W. E., Acree M., Stewart A., Silas J., Jones A. (2018). The Multidimensional Assessment of Interoceptive Awareness, Version 2 (MAIA-2). *PLoS One*, 13(12): e0208034.

Muhtadie, L. (2017). *Emotional Response Coherence and Interoceptive Awareness: Development and Validation of a Novel Assessment Method* [PhD diss.]. UC Berkeley Electronic Theses and Dissertations. https://escholarship.org/uc/item/14z3k333

Murphy, J. (2022). Propensity to use interoceptive signals: An important individual difference. *Biological Psychology*, *171*, 108326. https://doi.org/10.1016/j.biopsycho.2022.108326

Murphy, J., Brewer, R., Catmur, C., & Bird, G. (2017). Interoception and psychopathology: A developmental neuroscience perspective. *Developmental Cognitive Neuroscience*, *23*, 45-56.

Murphy, J., Catmur, C., & Bird, G. (2019). Classifying individual differences in interoception: Implications for the measurement of interoceptive awareness. *Psychonomic Bulletin & Review*, *26*(5), 1467–1471. https://doi.org/10.3758/s13423-019-01632-7

Murphy, J., Millgate, E., Geary, H., Ichijo, E., Coll, M. P., Brewer, R., ... & Bird, G. (2018).

Knowledge of resting heart rate mediates the relationship between intelligence and the heartbeat counting task. *Biological Psychology*, *133*, 1-3.

Pace-Schott, E. F., Amole, M. C., Aue, T., Balconi, M., Bylsma, L. M., Critchley, H., Demaree, H. A., Friedman, B. H., Gooding, A. E. K., Gosseries, O., Jovanovic, T., Kirby, L. A. J., Kozlowska, K., Laureys, S., Lowe, L., Magee, K., Marin, M.-F., Merner, A. R., Robinson, J. L., … VanElzakker, M. B. (2019). Physiological feelings. *Neuroscience & Biobehavioral Reviews*, *103*, 267–304. https://doi.org/10.1016/j.neubiorev.2019.05.002

Papousek, I., Paechter, M., Weiss, E. M., & Lackner, H. K. (2017). The tendency to ruminate and the dynamics of heart rate recovery after an ordinary, mildly stressful performance situation. *Personality and Individual Differences*, *104*, 150-154.

Paulus, M. P., Feinstein, J. S., & Khalsa, S. S. (2019). An Active Inference Approach to Interoceptive Psychopathology. *Annual Review of Clinical Psychology*, *15*(1), 97–122. https://doi.org/10.1146/annurev-clinpsy-050718-095617

Radloff, L. S. (1977). The CES-D scale: A self-report depression scale for research in the general population. Applied Psychology Measurement, 1(3), 385-401.

Ring, C., & Brener, J. (1996). Influence of beliefs about heart rate and actual heart rate on heartbeat counting. *Psychophysiology*, *33*(5), 541-546.

Ryff, C. D. (1989). Happiness is everything, or is it? Explorations on the meaning of psychological wellbeing. J*ournal of Personality and Social Psychology*, 57, 1069-1081.

Schandry, R. (1981). Heart Beat Perception and Emotional Experience. *Psychophysiology*, *18*(4), 483–488. https://doi.org/10.1111/j.1469-8986.1981.tb02486.x

Selye, H. (1975). Stress and distress. *Comprehensive Therapy*, *1*(8), 9-13.

Shields, S., Mallory, M., & Simon, A. (1989). Shields_1989_Body Awareness Questionnaire.pdf. *Journal of Personality Assessment*, *53*(4), 802–815.

Siegel, E. H., Sands, M. K., Van den Noortgate, W., Condon, P., Chang, Y., Dy, J., ... & Barrett, L. F. (2018). Emotion fingerprints or emotion populations? A meta-analytic investigation of autonomic features of emotion categories. *Psychological bulletin*, *144*(4), 343.

Sommerfeldt, S. L., Schaefer, S. M., Brauer, M., Ryff, C. D., & Davidson, R. J. (2019). Individual differences in the association between subjective stress and heart rate are related to psychological and physical well-being. *Psychological Science*, *30*(7), 1016-1029.

Sommerfeldt, S. L., Brauer, M., Pedersen, W. S., Ryff, C. D., Davidson, R. J., & Schaefer, S. M. (in prep). Individual differences in the association between subjective stress and heart rate are related to lower stress context and higher psychological well-being.

Sommerfeldt, S. L. (2019, November 8). Stress-physiology Coherence, Interoception, and Mindfulness - Baseline Data. Retrieved from osf.io/m3bzy

Sommerfeldt, S. L. (2021a, October 24). Stress-physiology Coherence, Interoception, and Mindfulness - Mindfulness Intervention. Retrieved from osf.io/76qpu

Sommerfeldt, S. L. (2021b, October 26). Stress-physiology Coherence, Interoception, and Mindfulness - Neutral Faces Task. Retrieved from osf.io/2vkms

Spielberger, C. D. (1983). Manual for the state-trait anxiety inventory (Form Y) ("Self-evaluation questionnaire"). *Consulting Psychologists Press*, Palo Alto, CA.

Spitzer, R. L., Kroenke, K., Williams, J. B., & Löwe, B. (2006). A brief measure for assessing g generalized anxiety disorder: the GAD-7. *Archives of Internal Medicine*, *166*(10), 1092-1097.

Stroop, J. R. (1935). Studies of interference in serial verbal reactions. *Journal of experimental psychology*, *18*(6), 643.

Suksasilp, C., & Garfinkel, S. N. (2022). Towards a comprehensive assessment of interoception in a multi-dimensional framework. *Biological Psychology*, *168*, 108262. https://doi.org/10.1016/j.biopsycho.2022.108262

Sze, J. A., Gyurak, A., Yuan, J. W., & Levenson, R. W. (2010). Coherence between emotional experience and physiology: Does body awareness training have an impact? *Emotion*, *10*(6), 803–814. https://doi.org/10.1037/a0020146

Terasawa, Y., Fukushima, H., & Umeda, S. (2011). How does interoceptive awareness interact with the subjective experience of emotion? An fMRI Study. *Human Brain Mapping*, n/a-n/a. https://doi.org/10.1002/hbm.21458

Trevisan, D. A., Altschuler, M. R., Bagdasarov, A., Carlos, C., Duan, S., Hamo, E., Kala, S., McNair, M. L., Parker, T., Stahl, D., Winkelman, T., Zhou, M., & McPartland, J. C. (2019). A meta-analysis on the relationship between interoceptive awareness and alexithymia: Distinguishing interoceptive accuracy and sensibility. *Journal of Abnormal Psychology*, *128*(8), 765–776. https://doi.org/10.1037/abn0000454

Turner, J. R., Hewitt, J. K., Morgan, R. K., Sims, J., Carroll, D., & Kelly, K. A. (1986). Graded mental arithmetic as an active psychological challenge. *International Journal of Psychophysiology*, *3*, 307-309. https://doi.org/10.1016/0167-8760(86)90039-5

Turner, J. R., Sims, J., Carroll, D., Morgan, R. K., & Hewitt, J. K. (1987). A comparative evaluation of heart rate reactivity during MATH and a standard mental arithmetic task. *International Journal of Psychophysiology*, *5*, 301-303. https://doi.org/10.1016/0167-8760(87)90061-4

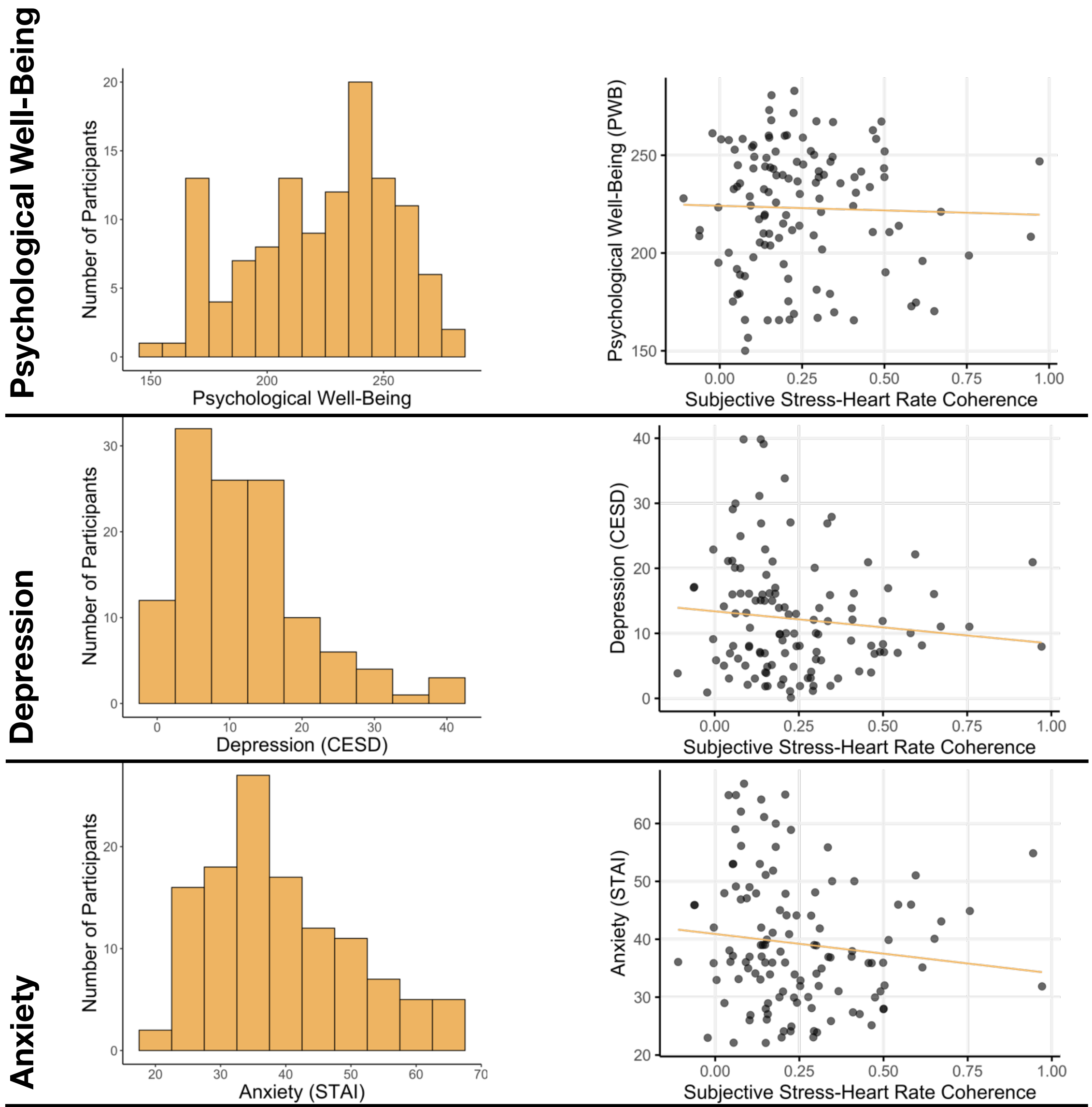
Van Dam, N. T., Earleywine, M., & Danoff-Burg, S. (2009). Differential item function across meditators and non-meditators on the Five Facet Mindfulness Questionnaire. *Personality and Individual Differences*, *47*(5), 516-521.

Watson, D., Clark, L. A., & Tellegen, A. (1988). Development and validation of brief measures of positive and negative affect: the PANAS scales. *Journal of Personality and Social Psychology*, 54(6), 1063.

Yates, A. J., Jones, K. E., Marie, G. V., & Hogben, J. H. (1985). Detection of the heartbeat and events in the cardiac cycle. *Psychophysiology*, *22*(5), 561-567.

Appendix A

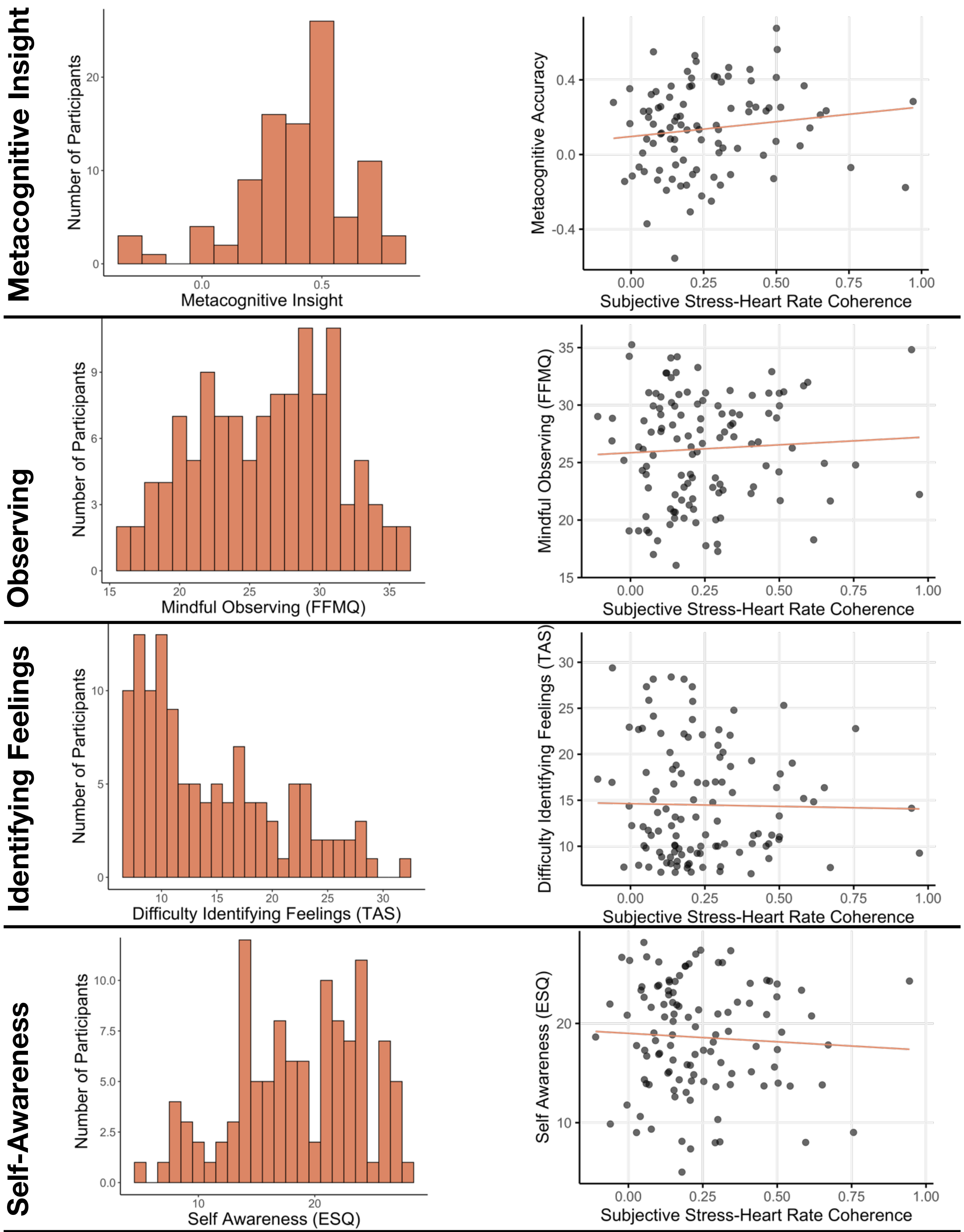
Well-Being Measures Relations to Subjective Stress-Heart Rate Coherence



Note. To visualize participant-level data, Subjective Stress-Heart Rate Coherence is represented by extracted BLUPs in scatterplots. These extracted measures were not used in analyses of these relations.

Appendix B

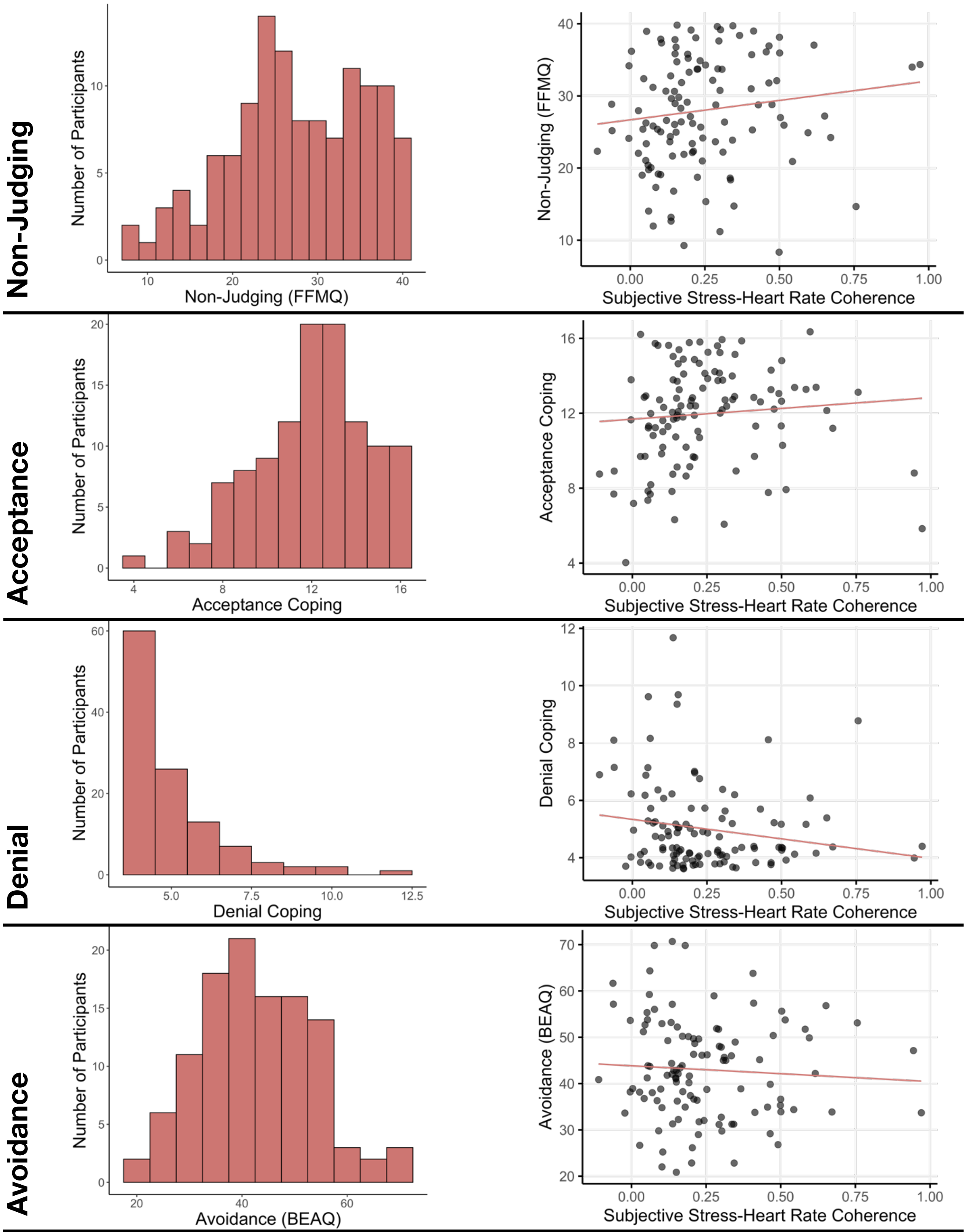
Awareness Measures Relations to Subjective Stress-Heart Rate Coherence



Note. To visualize participant-level data, Subjective Stress-Heart Rate Coherence is represented by extracted BLUPs in scatterplots. These extracted measures were not used in analyses of these relations.

Appendix C

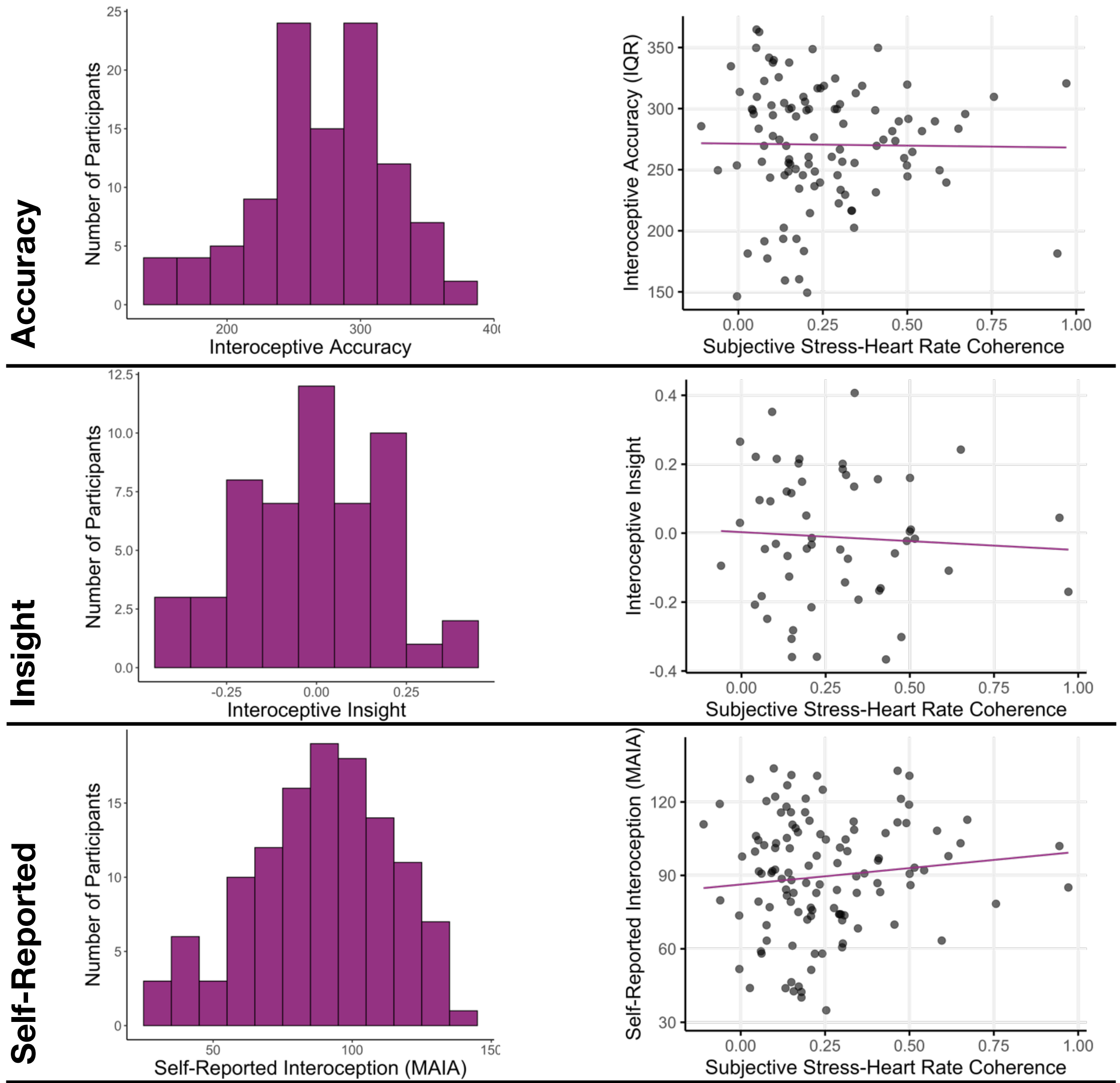
Acceptance Measures Relations to Subjective Stress-Heart Rate Coherence



Note. To visualize participant-level data, Subjective Stress-Heart Rate Coherence is represented by extracted BLUPs in scatterplots. These extracted measures were not used in analyses of these relations.

Appendix D

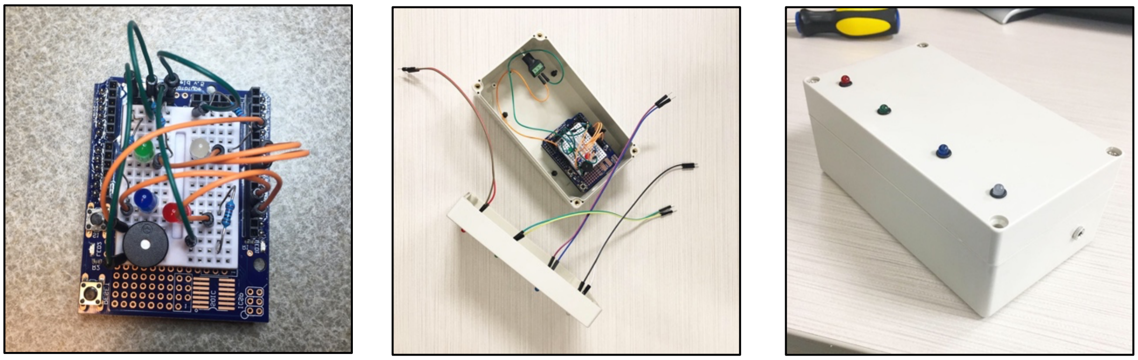
Interoceptive Measures Relations to Subjective Stress-Heart Rate Coherence



Note. To visualize participant-level data, Subjective Stress-Heart Rate Coherence is represented by extracted BLUPs in scatterplots. These extracted measures were not used in analyses of these relations.

Appendix E

Method of Constant Stimuli Task Hardware



Note. Arduino hardware through phases of development. Participants saw the version on the right.

Appendix F

Exploratory Group x Time Analyses of Intervention Effects

	b	SE	*F*	error *df*	*p*
Well-Being					
PWB	2.336	2.82	0.69	91	.410
Depression	-2.200	1.43	2.36	91	.128
Anxiety	-3.070	1.14	7.26	91	.008*
Interoception					
Accuracy	-10.763	10.88	0.98	64	.326
Insight	-0.047	0.06	.524	24	.476
Self-Reported (MAIA)	11.680	3.59	10.61	91	.002*
MAIA Subscales					
Attention Regulation	2.667	1.14	5.50	91	.021*
Noticing	0.078	0.75	0.01	91	.918
Not Distracting	0.965	1.02	0.89	91	.347
Not Worrying	0.565	0.64	0.77	91	.381
Emotional Awareness	2.608	0.93	7.80	91	.006*
Self Regulation	2.188	0.73	8.89	91	.004*
Body Listening	1.400	0.50	7.98	91	.006*
Trusting	0.583	0.49	1.40	91	.240
FFMQ Subscales					
Awareness	-0.289	0.80	0.13	91	.718
Describing	-0.282	0.60	0.23	91	.636
NonReactivity	1.519	0.65	5.49	91	.021*
Perceived Stress (PSS-10)	-1.58	0.95	2.77	91	.100
Internal Locus of Control	0.599	1.00	0.36	90	.550
Cognitive Fusion	-1.771	1.11	2.53	86	.116
Emotional Spillover	-0.036	0.038	0.88	85	.350
Mindset	-1.767	1.05	2.84	74	.096