

The Mechanism by Which Mindfulness Sustains Adaptation: Preliminary Evidence from Heart Rate Variability Self-Similarity Postprint

Authors: Sun Shasha, Li Xiaobing, Li Baoshan, Liu Chengyi, Huang Miner

Date: 2018-09-07T00:00:00+00:00

Abstract

Introducing self-similarity algorithms to characterize the process of functional homeostasis, this study explores the relationship between trait mindfulness and heart rate variability (HRV) self-similarity across different conditions from the perspective of functional homeostasis, aiming to reveal the potential mechanisms underlying mindfulness effects. Functional homeostasis refers to the capacity of an organism to maintain relatively stable functioning amidst changes in internal and external environments. The study established four distinct conditions: resting state, cold pressor task, post-cold-pressor recovery, and mindfulness practice, and recorded participants' HRV metrics across these four stages. Results demonstrated a significant correlation between HRV self-similarity and trait mindfulness, with the high HRV self-similarity group exhibiting higher values across all HRV indices during the cold pressor task compared to the low HRV self-similarity group. These findings suggest that the physiological mechanisms through which mindfulness maintains adaptive functioning may be associated with functional homeostasis.

Full Text

Physiological Mechanisms of Mindfulness: Preliminary Evidence from Self-Similarity of Heart Rate Variability

SUN Shasha¹, LI Xiaobing², LI Baoshan¹, LIU Chengyi³, HUANG Miner¹

(¹ Department of Psychology, Sun Yat-sen University, Guangzhou 510006, China)

(² Department of Physical Education, Sun Yat-sen University, Guangzhou 510275, China)

(³ School of Physical Education and Sports Science, South China Normal University, Guangzhou 510006, China)

Abstract

This study introduces a self-similarity algorithm to characterize the process of function-specific homeostasis and explores the relationship between trait mindfulness and heart rate variability (HRV) self-similarity across different conditions to reveal the potential mechanisms through which mindfulness exerts its effects. Function-specific homeostasis refers to the capacity of an organism to maintain relatively stable functioning in response to internal and external environmental changes. The study established four distinct conditions: resting state, cold-pressor task, post-cold-pressor recovery, and mindfulness practice, while recording participants' HRV indicators across these four phases. Results demonstrated a significant correlation between HRV self-similarity and trait mindfulness, with the high HRV self-similarity group exhibiting higher HRV metrics during the cold-pressor task compared to the low self-similarity group. These findings suggest that the physiological mechanisms through which mindfulness maintains adaptive functioning may be related to function-specific homeostasis.

Keywords: trait mindfulness; self-similarity; function-specific homeostasis; heart rate variability

Classification: B845; R395

Introduction

The concept of “mindfulness,” derived from Buddhist philosophy, has garnered increasing attention in recent years. At the research level, the number of publications on mindfulness has grown exponentially over the past two decades; at the application level, mindfulness has been increasingly implemented across clinical, educational, management, and athletic domains. What exactly does mindfulness refer to? What are its effects? And what mechanisms underlie these effects? The following sections review the literature on mindfulness' s role in promoting health and adaptation and its physiological mechanisms, identify limitations in previous research, and propose the current study' s rationale.

1.1 Concept and Effects of Mindfulness

Mindfulness refers to the conscious, non-judgmental awareness of the present moment (Kabat-Zinn, 1994). It is a process emphasizing openness and acceptance of present-moment experience (Baer, Smith, & Allen, 2004; Bishop et al., 2004; Brown & Ryan, 2003; Chambers, Gullone, & Allen, 2009) and comprises a series of techniques for cultivating present-moment awareness (Didonna, 2009). As a self-regulatory approach for maintaining health and adaptation, mindfulness has received growing attention. Since Kabat-Zinn' s (1982) seminal study on mindfulness for chronic pain relief, numerous investigations have supported its beneficial effects on health and adaptation (Eberth & Sedlmeier,

2012; Grossman, Niemann, Schmidt, & Walach, 2004; Keng, Smoski, & Robins, 2011; Sedlmeier et al., 2012). As an intervention, mindfulness can reduce depression relapse (Godfrin & van Heeringen, 2010), enhance emotion regulation in individuals with social anxiety (Goldin & Gross, 2010), decrease alcohol relapse (Vieten, Astin, Buscemi, & Galloway, 2010), improve physical health in diabetic patients (Hartmann et al., 2012), facilitate psychosocial adjustment in cancer patients (Henderson et al., 2012), and maintain immune system function in HIV-positive individuals (Creswell, Myers, Cole, & Irwin, 2009). As a psychological trait, mindfulness predicts greater relationship satisfaction (Barnes, Brown, Krusemark, Cambell, & Rogge, 2007) and enhanced well-being and work engagement (Malinowski & Hui, 2015).

Trait mindfulness reflects an individual's adaptive tendency to focus attention on the present moment and engage in self-regulation (Weinstein, Brown, & Ryan, 2009). Individuals high in trait mindfulness adopt a more accepting, non-judgmental attitude toward their experiences, utilize a decentered perspective, and are better able to view their thoughts and emotions as mental events rather than accurate representations of reality (Shapiro, Carlson, Astin, & Freedman, 2006). Consequently, relative to those low in trait mindfulness, high-trait-mindfulness individuals can make more flexible and effective adjustments in response to environmental changes. While some researchers conceptualize trait mindfulness as a unidimensional structure related to attention and awareness (Brown & Ryan, 2003), others argue for a multidimensional structure encompassing both attention/awareness and non-judgmental acceptance of internal experiences (Sauer et al., 2013). Despite these definitional differences, research consistently demonstrates that high trait mindfulness is associated with greater adaptability in self-regulation (Siegling & Petrides, 2014).

1.2 Mechanisms of Mindfulness in Maintaining Health and Adaptation

How does mindfulness maintain and promote adaptation? What are its underlying physiological mechanisms? Researchers have proposed that mindfulness enhances prefrontal cortex regulation, reduces secretion of cortisol, epinephrine, and norepinephrine via the HPA (hypothalamic-pituitary-adrenocortical) and SAM (sympathetic-adrenomedullary) axes, attenuates stress responses, and decreases stress-related disease risk (Creswell & Lindsay, 2014; Creswell, 2015). The autonomic nervous system (ANS) serves as an automated stress response regulation system (Thayer & Lane, 2000), and mindfulness may influence ANS function by modulating cardiovascular stress responses (Demarzo et al., 2014).

Heart rate variability (HRV) marks ANS regulatory function, reflecting the brain's control over behavior and peripheral physiology (Thayer, Åhs, Fredrikson, Sollers, & Wager, 2012) and serving as a robust biomarker of individual adaptation (Force, 1996; Thayer et al., 2012; Thayer & Lane, 2000, 2009; Thayer & Brosschot, 2005). Greater HRV indicates a larger range of heart rate variation and stronger adaptability of the cardiovascular system, whereas weaker

HRV suggests insufficient ANS capacity to respond to changing environments, increasing disease risk (Thayer & Wothunsky, Pilver, & Brewer, 2012; Krygier et al., 2013). Thus, HRV improvement may represent an important physiological mechanism through which mindfulness promotes adaptation. Current linear quantification methods for HRV can be broadly categorized into time-domain and frequency-domain analyses (Berntson et al., 1997). Commonly used time-domain indices include: SDNN (the standard deviation of normal NN intervals), which reflects overall HRV variation (Shaffer, McCraty, & Zerr, 2014), and RMSSD (the root mean square of successive differences between normal heartbeats), which reflects beat-to-beat variation and primarily assesses parasympathetic activity (Kleiger, Stein, & Bigger, 2005). Frequency-domain analysis decomposes total power (TP) into low-frequency (LF, 0.04–0.15 Hz) and high-frequency (HF, 0.15–0.40 Hz) components based on power spectral density (PSD). LF-HRV is generally considered to reflect sympathetic activity, while HF-HRV reflects parasympathetic activity (Berntson et al., 1997; Billman, 2011). The LF/HF ratio quantifies the relationship between sympathetic and parasympathetic activity (Pagani et al., 1984). Coherence, a recently proposed frequency-domain metric, reflects interactions among respiration, blood pressure, and cardiac rhythms, as well as synchronization between systems (e.g., EEG rhythms and cardiac cycles) or system resonance (Shaffer et al., 2014; McCraty & Childre, 2010).

Some researchers have examined mindfulness' s adaptive mechanisms from a homeostasis perspective, noting that stress disrupts homeostasis through functional dysregulation of the anterior cingulate cortex (ACC, Tirsch, 2010), ANS (Hosemans, 2015), and cortisol secretion (Matousek, Dobkin, & Pruessner, 2010). Through mindful awareness, individuals can monitor bodily sensations arising from internal and external stimuli in real time, better evaluate their environment and challenges, adjust their states to cope with environmental changes, re-establish homeostasis, and adapt to new circumstances rather than remaining in chronic stress states. In other words, mindfulness enables individuals to maintain allostatic regulation when facing complex environments, allowing functions such as ACC, ANS, and cortisol secretion to operate stably and facilitating more adaptive behavioral responses (Fletcher, Schoendorff, & Hayes, 2010; Matousek et al., 2010; Fries, 2007). Anger, as an emotion, plays an important role in mobilizing psychological resources and maintaining self-esteem, yet it is also considered one of the most destructive emotions, harming both the angry individual and others (Wright, Day & Howells, 2009). Novaco (2007) posits that anger is a learned, automatic coping style, with self-monitoring at the core of anger regulation: “Only when individuals detect signals deviating from homeostasis can they correct such deviations.” Mindfulness allows individuals to detect anger-related cues promptly and respond more appropriately, thereby avoiding problems arising from automatic reactions (Wright et al., 2009). Chrisman, Christopher, and Lichtenstein (2009) conducted a qualitative study using Qigong as a mindfulness practice method, providing 15 weeks of Qigong training to graduate counseling students. Results showed improvements in physical, emo-

tional, and psychological domains, including better balance, deeper breathing, greater emotional calmness, enhanced attention, and clearer consciousness. The authors explained Qigong' s mechanisms from a Traditional Chinese Medicine “Qi” perspective, proposing that disease results from Qi imbalance and blockage that disrupts homeostasis, whereas long-term Qigong practice removes blockages, facilitates smooth Qi flow throughout the body, restores inherent homeostasis, and ultimately achieves physical and mental health. Other researchers suggest that weak positive reappraisal capacity leads individuals to perceive insufficient resources when facing challenges; this stress appraisal pattern prolongs and overactivates the HPA axis, disrupts systemic homeostasis, and ultimately causes disease (Rosmond, 2005). Mindfulness can enhance positive reappraisal capacity and plays a central role in the reappraisal process, thereby reducing stress-related disease risk (Garland, Gaylord, & Park, 2009). These studies demonstrate that researchers have used the “homeostasis” concept to explain mindfulness' s role in maintaining adaptation, yet no effective method has been available to quantify the “homeostasis” process. Therefore, this study attempts to introduce a novel algorithm to characterize this process, which will be detailed below.

Previous research has found close relationships between trait mindfulness and HRV changes during emotion regulation. Braeken, Otte, Nyklicek, and Van den Bergh (2012) examined trait mindfulness and HRV (RMSSD, HF) in 150 pregnant women across five conditions: resting state, mental arithmetic task, picture relaxation, mental arithmetic task, and music relaxation. Results showed that pregnant women with high trait mindfulness exhibited higher HRV during both resting and mental arithmetic states compared to those with low trait mindfulness. Garland (2011) assessed trait mindfulness, alcohol attentional bias, and HRV (HF) in 58 alcohol-dependent inpatients, finding that high-trait-mindfulness individuals showed less attentional bias toward alcohol and higher HRV during the recovery phase after the task. Fogarty et al. (2015) induced negative emotions through a writing task and found that individuals high in trait mindfulness showed higher HRV (HF) during emotional recovery, indicating that trait mindfulness predicts better recovery following negative emotional reactions. Mankus, Aldao, Kerns, Mayville, and Mennin (2013) examined the relationship between trait mindfulness and HRV in individuals with high and low generalized anxiety during questionnaire completion, finding a significant correlation between trait mindfulness and HRV (MSD, mean of the absolute values of successive differences between adjacent heartbeats, a time-domain HRV index) only in the high-anxiety group.

However, some studies have failed to find significant correlations between trait mindfulness and HRV. Jäger (2016) found no significant correlation between trait mindfulness and resting-state HRV (SDNN, LF, VLF) in 106 university students. Soer, Jong, Hofstra, Preuper, and Reneman (2015) conducted three HRV coherence training sessions with 10 chronic musculoskeletal pain patients and 15 healthy controls, finding that although HRV coherence and trait mindfulness both improved pre- to post-training, the change in HRV coherence did

not significantly correlate with the change in trait mindfulness.

1.3 Problem Statement

HRV comprises numerous metrics, yet researchers examining trait mindfulness-HRV relationships have typically limited their selection to one or two indicators (e.g., Braeken et al., 2012; Jäger, 2016), with inconsistent metrics across studies. Moreover, previous research examining HRV changes across different phases (resting state, task state, post-task recovery) has not considered the coordinated relationships among indicators. For example, Braeken et al. (2012) analyzed correlations between HRV (RMSSD and HF) and trait mindfulness but did not examine the synergistic, systematic change patterns across multiple HRV indices. Consequently, previous studies have not comprehensively or systematically reflected the relationship between autonomic nervous system activity and trait mindfulness. The present study will introduce a more comprehensive set of HRV indicators and employ the concept and method of “self-similarity” to examine the relationship between the degree to which HRV indicators maintain self-similarity during change processes and individual trait mindfulness, attempting to reveal the physiological mechanisms underlying mindfulness.

Self-similarity refers to a pattern that remains invariant across spatial or temporal scales (Muzzio, Swanson, & Ottino, 1992), manifesting as a set repeating itself at different spatial or temporal scales (Galatzer-Levy, 1995). Self-similarity is ubiquitous in natural phenomena, such as plant growth and the relationship between ceramic fragment sizes. It also exists in psychoanalytic textual materials; Galatzer-Levy (1995) demonstrated that an obsessive-compulsive patient exhibited remarkably similar obsessive patterns across four time scales (minutes, hours, months, and years). If we understand HRV metric changes in specific states as certain distributions or sets, and if the coordinated relationships among HRV metrics exhibit temporal invariance or self-repetition across different states, then the HRV metrics are self-similar.

A system’s self-similarity characterizes the coordinated relationships among system parameters (also called indicators) (West, 2017). As shown in Equation (1), the self-similar coordinated relationship between two parameters in a change process is expressed by a power function (West, 2017). The exponent is called the self-similar exponent (SSE). The process logarithm with base ϕ (the golden ratio) is introduced for the two parameters across different states (Liu et al., 2016, 2017; Liu et al., 2017).

From Equation (1), we obtain that the absolute value of the process logarithm is called quantitative difference (QD, Liu et al., 2016, 2017; Liu et al., 2017). Equation (3) demonstrates that SSE can indeed characterize the coordinated relationship between two parameters.

The coordinated relationships among system parameters can manifest as the stability of overall system function. The biological significance of QD and self-similarity can be elaborated through function-specific homeostasis (FSH) and

allostasis, which refers to active adjustments that deviate from homeostasis to adapt to internal and external environmental changes (Liu et al., 2012, 2014; Sterling & Eyer, 1988) and represents a form of stability maintained during change processes (Sterling, 2012). Function-specific homeostasis and allostasis are negative feedback mechanisms that maintain stable function and ensure organismic adaptation to environmental changes. The distinction between function-specific homeostasis and homeostasis lies in that the latter emphasizes the stability of a single parameter, whereas the former emphasizes functional stability. Homeostasis of a single parameter can be studied by designing research targeting that parameter. In contrast, homeostasis of an organismic function is characterized by interactions among numerous parameters, which currently can only be revealed using self-similarity methods. We can hypothesize that mindfulness adjusts the interactive relationships among HRV parameters.

The significance threshold for each function's QD is denoted as (α, β) ; QD greater than α or β indicates significant or highly significant differences. Researchers (Liu et al., 2016, 2017; Liu et al., 2017) fitted epidemiological data and found that the QD significance threshold at the psychoneural level is (0.80, 1.22). The HRV indicators used in this study represent psychoneural-level functions; therefore, when $QD < 0.80$ among HRV indicators across different processes, the HRV indicators maintain self-similarity.

The above analysis demonstrates that the self-similarity algorithm can reveal the coordinated relationships among HRV indicators during dynamic change processes and characterize organismic function-specific homeostasis. Through mindful awareness, individuals can achieve stable and full functioning of their own capacities. Therefore, this study employs a self-similarity algorithm to quantify the concept and theory of function-specific homeostasis represented by HRV, exploring the relationship between trait mindfulness and HRV self-similarity to reveal the mechanisms through which mindfulness maintains adaptation. The research hypothesis posits a positive correlation between trait mindfulness and HRV self-similarity. Using healthy university students as participants, the study established four conditions: resting state, cold-pressor task, post-cold-pressor recovery, and mindfulness practice, recording participants' HRV across these four conditions to examine the relationship between trait mindfulness and HRV under different conditions. Specific research objectives were: (1) to present HRV changes in healthy university students across different states; (2) to explore the relationship between trait mindfulness and HRV across different states; and (3) to examine the relationship between trait mindfulness and HRV self-similarity during change processes.

Method

Participants

Fifty-six university students (41 females) from a Guangdong university were recruited through WeChat groups, aged 18-20 years ($M = 19.14$, $SD = 0.59$).

None had prior mindfulness practice or meditation experience.

Measures and Materials

2.2.1 Measurement Instrument The Mindful Attention Awareness Scale (MAAS) was used to measure trait mindfulness (Brown, Ryan, Loverich, Biegel, & West, 2011; Quaglia et al., 2016). Originally developed by Brown and Ryan (2003), the Chinese version was revised by Deng et al. (2012). The scale has a unidimensional structure with 15 items rated on a 6-point scale from 1 (almost always) to 6 (almost never), with higher scores indicating greater mindfulness. Sample items include: “I find myself preoccupied with the future or the past” and “I find it difficult to stay focused on what’s happening in the present.” Among various trait mindfulness measures, the MAAS is the most widely used (Park, Reilly-Spong, & Gross, 2013). Numerous studies have demonstrated good reliability and validity of the MAAS across different cultures and populations with varying meditation experience (Brown & Ryan, 2003; Carlson & Brown, 2005; Deng et al., 2012; MacKillop & Anderson, 2007). In the present study, the internal consistency coefficient for the 56 participants was 0.89.

2.2.2 Experimental Materials The mindfulness audio was the “Breathing Space” practice from the Android app Lingxi, authored by Tong Huiqi, with a duration of 5.4 minutes. The breathing space practice is a core exercise in Mindfulness-Based Cognitive Therapy (MBCT; Segal, Teasdale, Williams, & Gemar, 2002) and consists of three steps: awareness, gathering, and expanding (Segal, Williams, & Teasdale, 2012). Step one involves becoming aware of present-moment experience, including thoughts, emotions, and sensations; step two involves focusing attention on the sensations of breathing, particularly in the abdomen; step three involves expanding awareness from the breath to the entire body.

2.2.3 Experimental Apparatus The emWave Pro Plus system, developed by HeartMath, was used. The hardware consists primarily of an ear-clip sensor connected to a PC via USB, with software version 3.6.0.9625 for recording and converting heart rhythm data. The system has a sampling rate of 370 Hz and automatically detects and calibrates pulse waves. Metrics used included: average heart rate per minute (HR), common HRV time-domain indices SDNN and RMSSD, and common frequency-domain indices TP, LF-HRV, HF-HRV, LF/HF ratio, and coherence (see Introduction for specific meanings of HRV indices). Since both HR and HRV can represent autonomic nervous system activity, they were analyzed together.

The cold-pressor test is a safe and effective laboratory method for inducing pain (Zeltzer, Fanurik, & Lebaron, 1989). Equipment included a plastic bucket (diameter 22 mm, height 23 mm), an electronic thermometer, and an ice machine. Water temperature was adjusted to 4–6°C before the experiment (Liu, Wang,

Chang, Chen, & Si, 2013). Specific procedures are described in the research protocol in Section 2.3.

Procedure

Upon arrival, participants first completed an informed consent form approved by the university's ethics committee. They then scanned a QR code with WeChat to access Questionnaire Star, where they provided demographic information and completed the MAAS.

Participants were then brought to the laboratory and informed about the four experimental phases: 5 minutes resting, 3 minutes cold-pressor task, 5 minutes post-cold-pressor recovery, and 5.4 minutes mindfulness practice. After confirming participants' understanding, the experimenter launched the emWave Pro Plus software, attached the sensor to the participant's right earlobe, and began the formal experiment. The specific procedure is illustrated in [Figure 1: see original paper].

Phase 1: "5-minute heart rate recording at rest. Please sit comfortably in the chair, keep your head and body as still as possible, relax, remain alert, but do not think about anything."

Phase 2: "Cold-pressor test. This test measures pain tolerance, indicated by how long you can keep your hand in cold water. This is a safe and effective pain induction method commonly used in laboratories. You will place your left hand in the water with fingers spread, submerging up to the wrist. You may feel uncomfortable after placing your hand in the water, but we hope you can keep it there as long as possible. Generally, 1 minute is the minimum and 3 minutes the maximum. However, if you feel it is extremely unbearable or painful, you may click 'stop' at any time, remove your hand from the water, and end the experiment. After the experiment, please dry your hand with a tissue. When ready, place your hand in the water first, then click 'start' to begin."

Phase 3: "5-minute heart rate recording after the experiment. Please remain calm and relaxed, breathing naturally."

Phase 4: "Please follow the instructions in the audio recording."

The entire procedure lasted 35-45 minutes, with room temperature maintained at 19-22°C. Participants received extracurricular physical education credits or 15 RMB as compensation.

Data Processing: Self-Similarity Calculation

This study established four conditions: resting state (Phase 1), cold-pressor (Phase 2), post-cold-pressor recovery (Phase 3), and mindfulness practice (Phase 4). Phase 2 represents the stressful state, with HR and HRV metrics reaching their peaks (see [Figure 2: see original paper]), and was selected as the reference for calculations.

Specifically, HRV self-similarity calculation proceeded as follows:

Step 1: Using Equations (4) and (5), calculate the process logarithms of LF-HRV and HF-HRV for Phase 3 relative to Phase 2 and Phase 4 relative to Phase 2, yielding four process logarithms.

Step 2: Using Equation (6), calculate the self-similarity exponent (SSE) between the corresponding process logarithms for Phases 2-3 and Phases 2-4 for LF-HRV and HF-HRV, yielding two SSEs.

Step 3: Using Equation (7), calculate the quantitative difference (QD) between the two SSEs, yielding one QD. To maximize QD, the division method in Equation (6) was designed to ensure $SSE > 1$ whenever possible. This completes the self-similarity calculation for the LF-HRV and HF-HRV parameter pair across Phases 2-3 and Phases 2-4.

Step 4: Repeat Steps 1-3 to complete process logarithm, SSE, and QD calculations for all pairwise combinations of HR and HRV parameters, completing one participant's HRV self-similarity calculation.

Step 5: Repeat Steps 1-4 for all participants to complete HRV self-similarity calculations for the entire sample.

Since HRV activity represents psychoneural-level functioning, $QD < 0.80$ indicates that parameter pairs maintained self-similarity across different processes, whereas $QD > 0.80$ indicates they did not. This study employed eight parameters: HR and HRV indices (SDNN, RMSSD, TP, LF-HRV, HF-HRV, LF/HF ratio, and coherence). Calculations yielded $C(8,2) = (8 \times 7) / 2 = 28$ QDs per participant. Each participant's HRV self-similarity level was ultimately represented by the number of parameter pairs with $QD < 0.80$. Therefore, the final step was:

Step 6: Determine the number of HRV parameter pairs with $QD < 0.80$ for each participant.

Self-similarity calculations were performed using Excel 2010. Since both HR and HRV can represent autonomic nervous system activity and HR forms the basis for HRV calculation, "HRV self-similarity" in this paper refers to HRV self-similarity calculated with HR data included.

Results

Descriptive Statistics and Repeated Measures ANOVA of HRV Metrics Across Four Phases

Means and standard deviations of autonomic nervous system indices across the four phases are presented in .

Repeated measures ANOVA revealed significant differences across phases for HR, $F(3,165) = 28.14$, $p < 0.001$, $\eta^2 = 0.34$. Post-hoc tests indicated that HR during resting state was higher than during post-cold-pressor recovery and

mindfulness practice; HR during cold-pressor was higher than during resting, post-cold-pressor recovery, and mindfulness practice (see [Figure 3a: see original paper]).

Significant phase differences were found for SDNN, $F(3,165) = 11.02$, $p < 0.001$, $p^2 = 0.17$. Post-hoc tests showed SDNN during cold-pressor was higher than during resting, post-cold-pressor recovery, and mindfulness practice (see [Figure 3b: see original paper]).

RMSSD also showed significant phase differences, $F(3,165) = 15.56$, $p < 0.001$, $p^2 = 0.22$. Post-hoc tests revealed that RMSSD during cold-pressor was higher than during resting, post-cold-pressor recovery, and mindfulness practice, while RMSSD during mindfulness practice was lower than during resting and post-cold-pressor recovery (see [Figure 3c: see original paper]).

TP demonstrated significant phase differences, $F(3,165) = 6.45$, $p < 0.001$, $p^2 = 0.11$. Post-hoc tests indicated TP during cold-pressor was higher than during resting, post-cold-pressor recovery, and mindfulness practice (see [Figure 3d: see original paper]).

LF-HRV showed significant phase differences, $F(3,165) = 7.61$, $p < 0.001$, $p^2 = 0.12$. Post-hoc tests revealed LF-HRV during cold-pressor was higher than during resting, post-cold-pressor recovery, and mindfulness practice (see [Figure 3e: see original paper]).

HF-HRV exhibited significant phase differences, $F(3,165) = 7.99$, $p < 0.001$, $p^2 = 0.13$. Post-hoc tests showed HF-HRV during cold-pressor was higher than during resting, post-cold-pressor recovery, and mindfulness practice (see [Figure 3f: see original paper]).

The LF/HF ratio showed significant phase differences, $F(3,165) = 3.88$, $p = 0.010$, $p^2 = 0.07$. Post-hoc tests indicated the LF/HF ratio during mindfulness practice was higher than during resting, cold-pressor, and post-cold-pressor recovery (see [Figure 3g: see original paper]).

Coherence demonstrated significant phase differences, $F(3,165) = 6.04$, $p = 0.001$, $p^2 = 0.10$, with coherence during mindfulness practice higher than during resting, cold-pressor, and post-cold-pressor recovery (see [Figure 3h: see original paper]).

Correlations Between Trait Mindfulness and Autonomic Nervous System Indices Across Four Phases

The mean MAAS total score for the 56 participants was 51.64 ± 12.14 . Pearson correlation results (see) showed that MAAS total score did not significantly correlate with any resting-state autonomic nervous system indices, nor with indices during mindfulness practice. However, MAAS total score significantly positively correlated with TP and HF-HRV during cold-pressor, and marginally positively correlated with RMSSD and LF-HRV during cold-pressor. Addition-

ally, MAAS total score significantly positively correlated with HF-HRV during post-cold-pressor recovery, and significantly negatively correlated with LF/HF ratio and coherence during post-cold-pressor recovery.

Relationship Between Trait Mindfulness and HRV Self-Similarity

In this study, the QD threshold for psychoneural-level functioning was 0.80, with parameter pair QD < 0.80 indicating self-similarity. The average number of parameter pairs meeting the QD threshold was 5.18 ± 4.30 , ranging from 0 to 18. MAAS total score significantly correlated with the number of parameter pairs meeting self-similarity criteria, Spearman's $r = 0.27$, $p = 0.047$.

To further analyze the relationship between HRV self-similarity and trait mindfulness and the influence of HRV self-similarity on HRV indices across phases, participants were divided into groups based on HRV self-similarity. Those with 5 self-similar parameter pairs were classified as low self-similarity ($n = 31$, MAAS = 48.64 ± 9.91), and those with >5 pairs as high self-similarity ($n = 25$, MAAS = 55.36 ± 13.75). Independent samples t-test revealed a significant difference in MAAS total scores between high and low self-similarity groups, $t(54) = 2.12$, $p = 0.038$, Cohen's $d = 0.57$ (see [Figure 4: see original paper]).

Differences in HRV Indices Across Phases Between High and Low Self-Similarity Groups

Means and standard deviations of HRV indices across phases for high and low self-similarity groups are presented in .

Repeated measures ANOVA revealed a significant main effect of phase on SDNN, $F(3,162) = 13.40$, $p < 0.001$, $p^2 = 0.20$, and a significant interaction between self-similarity group and phase, $F(3,162) = 5.06$, $p = 0.002$, $p^2 = 0.09$. Simple effects analysis showed that the high self-similarity group had higher SDNN than the low self-similarity group during cold-pressor, $F(1,54) = 6.84$, $p = 0.019$, $p^2 = 0.10$, with no significant group differences in other phases (see [Figure 5a: see original paper]).

A significant main effect of phase on RMSSD was found, $F(3,162) = 18.09$, $p < 0.001$, $p^2 = 0.25$, with a significant group \times phase interaction, $F(3,162) = 4.20$, $p = 0.007$, $p^2 = 0.07$. Simple effects analysis revealed higher RMSSD in the high self-similarity group during cold-pressor, $F(1,54) = 6.76$, $p = 0.012$, $p^2 = 0.11$, with no group differences in other phases (see [Figure 5b: see original paper]).

TP showed a significant main effect of phase, $F(3,162) = 8.47$, $p < 0.001$, $p^2 = 0.14$, and a significant group \times phase interaction, $F(3,162) = 6.30$, $p < 0.001$, $p^2 = 0.10$. Simple effects analysis indicated higher TP in the high self-similarity group during cold-pressor, $F(1,54) = 6.65$, $p = 0.01$, $p^2 = 0.11$, with no group differences in other phases (see [Figure 5c: see original paper]).

LF-HRV demonstrated a significant main effect of phase, $F(3,162) = 9.47$, $p < 0.001$, $p^2 = 0.15$, and a significant group \times phase interaction, $F(3,162) = 4.76$, $p = 0.003$, $p^2 = 0.08$. Simple effects analysis showed higher LF-HRV in the high self-similarity group during cold-pressor, $F(1,54) = 4.19$, $p = 0.045$, $p^2 = 0.20$, with no group differences in other phases (see [Figure 5d: see original paper]).

HF-HRV exhibited a significant main effect of phase, $F(3,162) = 9.84$, $p < 0.001$, $p^2 = 0.15$, and a significant group \times phase interaction, $F(3,162) = 4.74$, $p = 0.003$, $p^2 = 0.08$. Simple effects analysis revealed higher HF-HRV in the high self-similarity group during cold-pressor, $F(1,54) = 6.18$, $p = 0.016$, $p^2 = 0.10$, with no group differences in other phases (see [Figure 5e: see original paper]).

Discussion

The role of mindfulness in maintaining adaptation has been well-documented, with numerous studies exploring its underlying mechanisms. This study focused on the relationship between trait mindfulness and autonomic nervous system activity, using HRV as an indicator of autonomic function. Previous research has been limited to a few HRV indices (e.g., Braeken et al., 2012; Jäger, 2016) and has not considered the coordinated relationships among indices across different states. We argue that as a system, the coordinated interactions among multiple indices better reflect, comprehensively and systematically, the organism's adaptation process. Additionally, while previous studies have used the "homeostasis" concept to explain mindfulness's adaptive role (e.g., Chrisman et al., 2009; Hosemans, 2015; Wright et al., 2009), they have not quantified the homeostasis process. This study introduced a self-similarity algorithm and the concept of function-specific homeostasis, quantifying function-specific homeostasis of autonomic nervous system activity by calculating coordinated relationships among HR and HRV indices across different phases. This represents the first application of this quantification method in psychological research, advancing previous work.

The study yielded several key findings. Most importantly, MAAS total score significantly positively correlated with HRV self-similarity across the cold-pressor to post-cold-pressor recovery and cold-pressor to mindfulness practice processes, supporting our hypothesis. This result indicates that higher trait mindfulness is associated with greater maintenance of autonomic nervous system function self-similarity when facing different stimuli. The biological significance of self-similarity lies in maintaining allostasis during environmental changes, meaning high self-similarity individuals can real-time adjust their physical and mental states to adapt to current environmental changes based on their function-specific homeostasis, without over-activating or under-activating functions beyond certain limits. The MAAS measures individual attention and awareness capacity; mindful awareness allows individuals to detect subtle changes in bodily signals and environmental stimuli to respond most appropriately. The high self-similarity group had significantly higher MAAS scores than the low self-similarity group (see [Figure 4: see original paper]), and showed higher HRV in-

indices (SDNN, RMSSD, TP, LF, and HF) during cold-pressor (see [Figure 5: see original paper]). Higher HRV indicates better brain control over peripheral physiology and better adaptation (Force, 1996; Thayer & Lane, 2000, 2009; Thayer et al., 2012; Thayer & Brosschot, 2005). Combined, these results suggest that individuals with high HRV self-similarity exhibit higher trait mindfulness, maintain function-specific homeostasis across changes, and show more adaptive responses. This also demonstrates that grouping participants by HRV self-similarity was effective and necessary. As shown in [Figure 5: see original paper], during cold-pressor, the high HRV self-similarity group had significantly higher HRV indices than the low self-similarity group, while no group differences emerged during post-cold-pressor recovery. This suggests the low self-similarity group did not respond to cold-pressor, whereas the high self-similarity group showed effective responses; during recovery, the high self-similarity group returned to baseline more quickly. The pattern of elevated HRV during cold-pressor and rapid recovery afterward reflects function-specific homeostasis and represents a self-limited process, referring to the organism's inherent self-healing capacity to automatically return to baseline without additional intervention (Bigelow, 1835). Previous research indicates that mindfulness does not reduce reactivity to stimuli but enables faster return to baseline after responding (Greenberg & Meiran, 2014). This suggests high-trait-mindfulness individuals, through real-time sensitive awareness of internal and external environments, can not only respond more effectively to environmental stimuli but also recover more rapidly afterward. Our results directly demonstrate that high HRV self-similarity individuals show stronger responses to cold-pressor and faster recovery. Although Section 3.3 showed a significant correlation between MAAS total score and HRV self-similarity, how mindfulness manifests the self-limited process (self-healing) during function-specific homeostasis maintenance requires further investigation.

The four-phase design allowed examination of autonomic nervous system activity across different states. Compared to resting, post-cold-pressor recovery, and mindfulness practice, HR and HRV indices (SDNN, RMSSD, TP, LF, and HF) were highest during cold-pressor, which appears inconsistent with previous findings. Earlier research has shown higher HRV during resting and self-regulation states compared to stress states (Grossman & Taylor, 2007) and higher HRV during mindfulness practice (Ditto, Eclache, & Goldman, 2006; Takahashi et al., 2005; Tang et al., 2009). Burg et al. (2012) suggested that higher HRV during mindfulness practice may result from deep relaxation associated with parasympathetic activation, which may explain why HRV did not increase during mindfulness practice in our study, as participants had no meditation experience and could not achieve deep relaxation when encountering a novel stimulus. Moses, Luecken, and Eason (2007) examined HRV changes from resting to task to recovery across three stress tasks—attention (pattern matching), cold-pressor, and speech—using HF-HRV and LF-HRV as indices. They found that during the attention task, task-state HF-HRV and LF-HRV were lower than resting state; however, during cold-pressor and speech tasks, changes in HF-HRV and LF-HRV relative to resting state were inconsistent. Specifically, during cold-

pressor, LF-HRV decreased while HF-HRV remained unchanged compared to resting state; during speech, LF-HRV remained unchanged while HF-HRV increased. This demonstrates that different stress tasks produce different HRV changes. Our results differ from Moses et al. (2007), who found decreased LF-HRV and unchanged HF-HRV during cold-pressor, whereas we found increased LF-HRV and HF-HRV. Moses et al. (2007) applied ice packs to participants' forearms for 2 minutes without reporting room temperature or other details. Our procedure required participants to immerse their right hand (up to the wrist) in 4–6°C water for 3 minutes at room temperature 19–22°C during December to January (Southern China's winter season). Whether these procedural differences account for the inconsistent HRV changes requires further verification. The higher HRV indices during our cold-pressor task suggest individuals were coordinating autonomic nervous system activity for self-regulation.

Another research question concerned relationships between trait mindfulness and HR/HRV indices across different states. Consistent with Jäger (2016), we found no significant correlations between trait mindfulness and resting-state HRV indices. We also found no significant correlations between trait mindfulness and HRV indices during post-cold-pressor recovery or mindfulness practice, despite coherence—a marker of harmonious and stable cardiac function—being highest during mindfulness practice, indicating that mindfulness practice did promote good cardiac state. Why didn't trait mindfulness correlate with HRV during mindfulness practice? One possible reason is that participants were university students with no mindfulness training or meditation experience; although mindfulness practice improved cardiac function, it remained a novel stimulus. Evans, Eisenlohr-Moul, Button, Baer, and Segerstrom (2014) used a cold-pressor task to induce acute pain, with control participants using their familiar pain coping methods and experimental participants following brief mindfulness instructions. They found that higher HRV predicted greater pain tolerance only in the control group, suggesting that for mindfulness-naïve individuals, mindfulness as an unfamiliar strategy may actually reduce pain tolerance.

Limitations and Future Directions

This study has several limitations. First, the sample consisted only of young university students, limiting generalizability to other age groups. Second, adaptation was indexed primarily by HRV without additional criterion variables. Third, the main finding was a correlation between trait mindfulness (MAAS total score) and HRV self-similarity, which does not imply causation.

Based on these findings and limitations, future research should proceed in two directions. First, having established a preliminary correlation between trait mindfulness and HRV self-similarity through the self-similarity algorithm, subsequent studies need to verify the stability of these results with larger datasets. For instance, whether replacing the physically-oriented cold-pressor task with more emotionally or cognitively oriented tasks would yield similar results requires further validation. Second, this study examined the relationship between trait

mindfulness and autonomic nervous system activity. Results tentatively suggest that mindfulness may maintain adaptation by preserving organismic function-specific homeostasis. Mindfulness originates from Buddhist philosophy, with formal practice termed “meditation.” Future research should compare autonomic nervous system activity during state transitions between experienced meditators and novices to more directly and deeply reveal the mechanisms through which mindfulness maintains adaptation.

Acknowledgments

We thank Dr. Tong Huiqi, author of the Lingxi app breathing space audio, for authorizing its use and providing support.

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