

Achieving is not maintaining: The temporal stability of heart rate variability during a slow breathing task

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Abstract

Background.

Slow breathing is widely recognized as an effective strategy for increasing parasympathetic activity and improving psychological functioning. However, successful regulation may involve more than simply reaching a desired physiological state. Equally important, and referred to here as physiological stability, is the ability to maintain that state over time, an aspect that has received substantially less empirical attention.

Methods.

Fifty-nine adults completed a five-minute baseline period followed by a ten-minute self-paced slow breathing exercise. Parasympathetic activity was assessed using Heart Rate Variability (HRV; root mean square of successive differences, RMSSD). Changes in RMSSD, its temporal stability during breathing, and associations with emotion regulation, resilience, and lifestyle factors were examined.

Results.

RMSSD was significantly higher during slow breathing than during baseline, indicating successful parasympathetic self-regulation. RMSSD instability was more prevalent during the breathing phase (69%) than during baseline (41%), a difference confirmed by McNemar's test. Exploratory analyses identified several associations with emotion regulation; however, after correction for multiple comparisons, only catastrophizing remained significantly associated with RMSSD instability ($r = .42$).

Conclusions.

Although HRV generally increased during slow breathing, many individuals exhibited HRV instability over time. These findings suggest that achieving and maintaining physiological regulation may represent distinct processes, underscoring the importance of temporal stability in breathing and HRV research. Moreover, catastrophizing was associated with a greater likelihood of HRV instability, suggesting that maladaptive emotion regulation may be linked to difficulties in maintaining physiological self-regulation.

1. INTRODUCTION

Few physiological processes are as fundamental to human survival as breathing. Although breathing is largely automatic, it remains one of the rare physiological functions that can be voluntarily controlled (Zaccaro et al., 2018). This unique ability to directly influence an otherwise autonomic process has made breathing a central focus of scientific research, particularly in the context of interventions designed to influence emotional, cognitive, and physiological functioning. Spontaneous breathing in adults often

happens at a breathing rate between 12 and 20 cycles per minute (Sherwood, 2006). In contrast, slow breathing is a technique where breathing is deliberately performed at a slower pace. Many studies have investigated the physiological and psychological benefits of slow breathing (Laborde et al., 2022; Lehrer et al., 2020; Russo et al., 2017; Zaccaro et al., 2018). Results indicate increases in heart rate variability (HRV), a commonly used marker of parasympathetic activity, during the breathing session, immediately following a single training session as well as after multi-session interventions (for a review, see Laborde et al., 2022). Importantly, these physiological changes appear to be accompanied by improvements in psychological functioning, including reductions in stress and anxiety, enhanced emotional well-being, and improved emotion regulation abilities (for a review, see Lehrer et al., 2020).

1.1 HRV as a marker of autonomic and psychological functioning

One of the primary pathways through which breathing exerts its effects is the autonomic nervous system. In particular, the vagus nerve, the main nerve of the parasympathetic nervous system (Brodal, 2016), is thought to play a central role in these effects. Accordingly, HRV has become one of the most frequently studied physiological markers in breathing research. HRV refers to the variability in the time intervals between consecutive heartbeats and is considered an important indicator of cardiac vagal activity, autonomic flexibility, and self-regulatory capacity (Berntson et al., 1997; Laborde et al., 2022). Higher levels of HRV are generally interpreted as reflecting greater autonomic flexibility and a stronger ability to adjust to physiological and psychological demands. In contrast, lower HRV has repeatedly been linked to maladaptive stress responses, cardiovascular health problems, and difficulties in emotion regulation (Beauchaine & Thayer, 2015; Mather & Thayer, 2018).

Furthermore, HRV is shaped by various individual characteristics and lifestyle factors, including sleep quality and duration, body mass index (BMI), and physical activity (Damoun et al., 2024; Sammito et al., 2024). Healthier lifestyle behaviors are generally associated with higher HRV and more adaptive autonomic functioning, whereas poor sleep, physical inactivity, and elevated BMI have been linked to reduced HRV (Sammito et al., 2024). Beyond lifestyle factors, HRV has also been consistently associated with psychological functioning, particularly emotion regulation. Higher HRV is typically linked to greater emotion regulation capacity and increased physiological flexibility in responding to stress and environmental demands (Mather & Thayer, 2018). Conversely, lower HRV has been associated with emotion regulation difficulties and increased vulnerability to stress-related outcomes. For example, Williams et al. (2015) demonstrated that individuals with lower resting vagally mediated HRV reported more frequent everyday difficulties in emotion regulation. Similarly, Berna et al. (2014) found that individuals with greater emotion regulation difficulties exhibited impaired cardiac vagal recovery following a negative emotional induction, suggesting reduced physiological flexibility in returning to a regulated state. Extending these findings to everyday life, Bylsma et al. (2024) showed that higher resting HRV was associated with less frequent use of avoidance-based emotion regulation strategies during a seven-day ecological momentary assessment study.

Together, these findings suggest that HRV is closely intertwined with individuals' capacity to regulate emotions effectively, both in laboratory and daily-life contexts. Similarly, resilience has been linked to more adaptive autonomic responding and greater parasympathetic regulation (Lee et al., 2024; Rösner et al., 2026). Individuals who are better able to cope with stress and adversity may therefore also be more capable of maintaining a regulated physiological state once it has been achieved.

1.2 Temporal stability of physiological regulation

Research on slow breathing has predominantly focused on average changes in HRV (Laborde et al., 2022). However, an increase in mean HRV does not reveal whether physiological responses remain stable throughout a breathing exercise or instead fluctuate substantially within individuals. As such, the temporal dynamics of HRV during slow breathing remain largely unexplored.

This distinction may be particularly relevant when individuals regulate their breathing independently. Although external pacing signals and biofeedback are frequently used in experimental and clinical settings (Laborde et al., 2022), individuals may also engage in breathing exercises without continuous guidance in everyday life. In such situations, maintaining a regulated physiological state may require ongoing self-monitoring and adjustment of breathing behavior. Despite the potential importance of these processes, little is currently known about the temporal stability of HRV during slow breathing or about the factors that may contribute to physiological stability and instability over time.

1.3 Current study

To address these gaps, the present exploratory study aimed to examine the temporal stability of parasympathetic self-regulation during a slow breathing exercise (i.e., whether a regulated state can be maintained over time). Importantly, rather than providing external pacing signals or biofeedback, participants were instructed to regulate their breathing independently (i.e., self-paced).

Three research questions were addressed. First, we examined whether participants were able to achieve parasympathetic self-regulation through self-paced slow breathing by comparing HRV during baseline and the breathing phase (Research Question 1, RQ1). We expected HRV to be higher during slow breathing than during baseline, reflecting increased parasympathetic activity (Laborde et al., 2022). Second, we investigated whether participants were able to maintain this physiological state over time by assessing the temporal stability of HRV during the breathing phase. To determine whether HRV instability was specific to self-paced slow breathing rather than reflecting natural fluctuations in HRV, the proportion of participants showing instability was compared between the self-paced slow breathing and baseline phases (RQ2). We expected that individuals would vary in their ability to maintain a stable physiological state throughout slow breathing. However, given the limited prior literature on this topic, no specific hypothesis was formulated regarding the relative prevalence of HRV instability. Finally, we explored whether HRV instability during self-paced slow breathing was associated with individual differences in habitual use of emotion regulation strategies, resilience, and lifestyle factors (RQ3). Based on prior literature linking HRV to psychological functioning (Mather & Thayer, 2018; Rösner et al., 2026), the ability to maintain a regulated physiological state was expected to be associated with more effective

emotion regulation (i.e. more use of adaptive strategies and less use of maladaptive strategies) and higher resilience.

2. METHOD

2.1 Ethics and participants

Ethical approval

was obtained from the Ethics Committee of the Faculty of Psychology and Educational Sciences of Ghent University (2023 – 110). The study was conducted in accordance with the Declaration of Helsinki and all participants gave their informed consent. The study design was preregistered on the Open Science framework (OSF; <https://osf.io/dbe3n>). Participants were compensated with €20 and received a psychoeducational video on stress and breathing (see Supplementary Materials), and their individual resonance frequencies. Participants were recruited through social media. In line with the guidelines of Laborde et al. (2017), participants with cardiovascular diseases or asthma, smokers and pregnant women were excluded. Furthermore, only participants aged between 18 and 65 years old could participate. A total of 62 participants were recruited. Two participants were excluded due to unusable physiological data and one participant due to protocol non-compliance. The final sample consisted of 59 participants. An overview of sample characteristics is provided in Table 1.

Table 1
Sample Characteristics (N = 59)

(Socio)demographic variables	
Age (M (SD))	34.63 years (12.04)
Gender (N, %)	Men (12, 20.34%), Women (46, 77.97%), Other (1, 1.69%)
BMI (M (SD))	23.26 (3.39)
Ethnicity (N, %)	Caucasian (59, 100%)
Employment (N, %)	Student (17, 28.81%), Employed full-time (29, 49.15%), Employed part-time (9, 15.25%), Unemployed (3, 5.08%), Occupationally disabled (1, 1.69%)
Sleep (M (SD))	7.64 hours per day (0.87)
Physical activity (M (SD))	3.62 hours per week (2.77)
Prior experience with breathing exercises (N, %)	No (23, 38.98%), Yes (36, 61.02%; e.g., yoga, box breathing)
Amount of practice (M(SD)) ^a	3.74 times per week (5.42)
Practice time (M (SD)) ^a	37.28 minutes per week (45.85)
<i>Note.</i> ^a These values are based on the subgroup that indicated having experience with breathing exercises (N = 36).	

2.2 Procedure

Participants attended two laboratory sessions and provided written informed consent at the start of the first session. Following confirmation of eligibility, participants completed demographic questions. Next, they were asked to remain seated in a fixed posture for seven minutes, to allow autonomic activity to stabilize following equipment attachment (Laborde et al., 2017), with the final five minutes serving as baseline. Participants then completed Visual Analogue Scales (VAS) about their current mood (i.e., tension, happiness, anxiety, and anger). Following this, abdominal breathing was explained to all participants, and they were given the opportunity to ask specific questions about the breathing technique. Once participants felt comfortable with abdominal breathing, they were instructed to slow down their breathing rate to a pace they personally experienced as most relaxing and to maintain this pace for 10 minutes. It was emphasized that no specific breathing rate was prescribed, participants were instead encouraged to relax while using abdominal breathing. Following the 10-minute self-paced slow breathing exercise, participants were asked to report any alternative techniques they had used during the breathing exercise and then completed questionnaires on emotion regulation and resilience. Next, participants' individual resonance frequency was subsequently determined, and a second session followed one week later. The present paper reports analyses based solely on data collected during the

first session. Resonance frequency and second-session data are addressed in a separate report (Depoorter et al., 2025), focusing on aim 1 of the preregistration (osf.io/db3n).

2.3 Materials

2.3.1 Questionnaires

To provide an accurate sample description, demographic information was collected: age, gender, self-reported height and weight (used to calculate BMI), ethnicity, and employment status. Furthermore, average sleep (hours per day) and physical activity (hours per week) were assessed. Lastly, participants' experience with breathing exercises (type and frequency) was assessed.

To assess emotion regulation, the short version of the Cognitive Emotion Regulation Questionnaire (CERQ-short; Garnefski & Kraaij, 2006) and the EMO-CHECK (Berking, 2017) were used. The CERQ-Short was used to assess cognitive emotion regulation strategies. The questionnaire consists of 18 items grouped into nine subscales: self-blame, other-blame, rumination, catastrophizing, positive refocusing, refocus on planning, positive reappraisal, putting into perspective, and acceptance. Participants rated each item on a 5-point Likert scale ranging from 1 (almost never) to 5 (almost always). Emotion regulation skills were assessed using the Dutch version of the Emotion Regulation Skills Questionnaire (EMO-CHECK; Berking, 2017; Grant et al., 2018). The instrument comprises 27 items evaluating perceived emotion regulation abilities during the previous two weeks. Responses were provided on a 5-point scale ranging from 0 (not at all) to 4 (almost always). The questionnaire contains nine subscales: awareness, sensations, clarity, understanding, acceptance, tolerance, confrontation, self-support, and modification. Self-reported resilience was measured using the Dutch 25-item version of the Connor-Davidson Resilience Scale (CD-RISC; Connor & Davidson, 2003). Participants rate each item on a scale from 0 (not true at all) to 4 (true nearly all of the time). Item scores were summed up to obtain a total resilience score ranging from 0 to 100, with higher scores indicating greater resilience. For each measure, internal consistency estimates for the present sample are reported in Table 2. With the exception of positive reappraisal (CERQ, $\alpha = .67$) and self-support (EMO-CHECK, $\alpha = .61$), internal consistency was acceptable to good across subscales ($\alpha = .72 - .88$). For a more detailed overview of measures and procedures, we refer to Depoorter et al. (2025).

Table 2
Descriptive statistics and Internal Consistency of questionnaires.

CERQ	M (SD)	Cronbach's alpha
Self-blame	2.46 (0.88)	.86
Other-blame	1.84 (0.73)	.86
Rumination	3.11 (1.03)	.74
Catastrophizing	1.86 (0.84)	.81
Positive refocusing	2.12 (0.89)	.82
Planning	3.31 (0.92)	.72
Positive reappraisal	3.16 (0.95)	.67
Putting into perspective	3.10 (1.04)	.81
Acceptance	2.99 (0.94)	.83
EMO-CHECK		
Awareness	2.47 (0.81)	.88
Sensations	2.79 (0.76)	.80
Clarity	2.84 (0.76)	.88
Understanding	2.94 (0.72)	.86
Acceptance	2.68 (0.66)	.77
Tolerance	2.49 (0.71)	.72
Confrontation	2.67 (0.69)	.76
Self-support	2.61 (0.59)	.61
Modification	2.25 (0.62)	.76
CD-RISC	66.71 (10.29)	.86

2.3.2 Psychophysiological measurements

The Vrije Universiteit Ambulatory Monitoring System device (VU-AMS; De Geus et al., 1995) was used to measure autonomic nervous system activity. This device simultaneously records an electrocardiogram (ECG) and impedance cardiography (ICG), making it possible to derive parasympathetic measures, including HRV indices, alongside respiratory parameters. For ECG three electrodes were placed on the participants' chest, whereas for ICG four electrodes were used (two on the chest and two on the back). Electrode placement is illustrated in Supplemental Fig. 1. The VU-AMS provides a range of autonomic

and respiratory measurements; however, only HRV variables were analyzed in the current study, given its focus on parasympathetic activity as the primary index of physiological self-regulation.

2.3.3 Data analysis

VU-AMS recordings were visually inspected, corrected and analyzed with the corresponding Data Analysis and Management Software (VU-DAMS) program version 5.4.13. Subsequent statistical analyses were conducted in R (version 4.5.1). Categorical data were described as counts, while continuous variables were summarized using means and standard deviations. Heart rate variability was operationalized using the root mean square of successive differences (RMSSD), a time-domain measure that primarily reflects parasympathetic activity and is among the most widely used HRV indices (Laborde et al., 2017). RMSSD was calculated using a 30-second moving window. For each RMSSD value, we used 30 seconds of consecutive heartbeats to obtain a stable and reliable estimate (Baek et al., 2015). The window then shifted forward by 10 seconds, after which RMSSD was recalculated. This resulted in a series of RMSSD estimates that balance temporal stability and temporal resolution.

To test whether individuals were able to achieve parasympathetic self-regulation through self-paced breathing (RQ1), RMSSD values during the baseline phase were compared with RMSSD values obtained during the first five minutes of the self-paced slow breathing phase using a Wilcoxon signed-rank test due to violations of the normality assumption. The first five minutes of the self-paced slow breathing phase were selected to match the duration of the five-minute baseline period, as effects of slow breathing on RMSSD have been demonstrated within the first minutes of practice (You et al., 2021). This allows for a direct, equally powered comparison between phases. Next, to evaluate the temporal stability of RMSSD, reflecting whether individuals were able to maintain a consistent level of regulation over time (RQ2), we applied the Ordinary Least Squares Cumulative Sum test (OLS-CUSUM; Brown et al., 1975; Ploberger & Kramer, 1992), using the 'strucchange' package (Zeileis et al., 2002). For each participant and phase (baseline vs. self-paced slow breathing), an intercept-only model was estimated, and the OLS-CUSUM procedure was used to assess whether mean RMSSD remained stable across the measurement period. Significant effects ($p < .05$) provide evidence of structural change (i.e., non-stationarity) within that particular phase for that participant. This approach allows the identification of participants who exhibited instability in RMSSD during the self-paced slow breathing phase, with the baseline phase serving as the within-person control condition. We relied on McNemar's test to examine whether the proportion of participants showing RMSSD instability differed between the self-paced slow breathing and baseline (i.e., control) phase. Finally, we explored whether RMSSD instability during the self-paced slow breathing phase was related to individual differences in indices of emotion regulation, resilience, and lifestyle factors (RQ3). For continuous variables, point-biserial correlations were computed between instability status (0 = stable, 1 = unstable) and the corresponding study variables. Associations with categorical variables were examined using Fisher's exact test or Pearson's Chi-square tests, as appropriate. Given the exploratory nature of these analyses and the number of statistical tests performed, p-values were additionally adjusted using the False Discovery Rate (FDR) procedure. A list of the used R packages, and relevant version information can be found in the supplementary material.

3. RESULTS

In total, 30.51% of the participants ($N = 18$) reported using other techniques than the instructed abdominal breathing during the self-paced slow breathing exercise. The most frequently reported strategies involved counting or pacing the breath, deliberately modifying the breathing pattern (e.g., extending exhalation relative to inhalation, or briefly holding the breath), and the use of mental cues or imagery (e.g., visualizing the abdomen as a balloon or silently repeating “in” and “out” during breathing).

3.1 RQ1: Effects of self-paced slow breathing on RMSSD

To examine whether participants were able to achieve parasympathetic self-regulation through self-paced slow breathing, RMSSD values obtained during the baseline phase were compared to those obtained during the self-paced slow breathing phase. A Wilcoxon signed-rank test revealed a significant difference in RMSSD during self-paced slow breathing compared to baseline ($V = 1468$, $p < .001$), with a large effect size ($r = .57$). RMSSD was significantly higher during the self-paced slow breathing phase ($Mdn = 39.69$, $IQR = 36.57$) than during baseline ($Mdn = 33.89$, $IQR = 22.78$; Fig. 1). These findings suggest that participants were generally able to increase parasympathetic activity during self-paced slow breathing.

3.2 RQ2: Instability of RMSSD

During the self-paced slow breathing phase, 69% ($N = 41$) of participants showed instability in RMSSD, whereas a minority demonstrated unstable RMSSD levels during the baseline phase (41%, $N = 24$). In total, 46% of participants ($N = 27$) exhibited instability during the self-paced slow breathing phase while having been stable during the baseline phase. Conversely, 17% ($N = 10$) showed instability during the baseline phase but stability during the self-paced slow breathing phase. Across both phases, 24% of participants ($N = 14$) consistently showed unstable RMSSD levels, whereas 13% ($N = 8$) consistently demonstrated stable RMSSD levels. McNemar’s test indicated that the proportion of participants showing instability differed significantly between the baseline and self-paced slow breathing phase ($\chi^2(1) = 7.81$, $p = .005$), with more participants becoming unstable during the self-paced slow breathing phase¹. This suggests that the instability observed during the self-paced slow breathing phase was not simply a continuation of pre-existing physiological fluctuations but appeared to be associated with the slow breathing task itself.

3.3 RQ3: Associations between RMSSD instability and clinical indices

To explore whether RMSSD instability during the self-paced slow breathing exercise was associated with emotion regulation, resilience, and lifestyle factors, point-biserial correlations were computed between instability status (0 = stable, 1 = unstable) and the corresponding study variables. The results are presented in Table 3. Several significant associations emerged. Higher levels of catastrophizing ($r = .42$, $p = .001$) and other-blame ($r = .26$, $p = .047$) were associated with a greater likelihood of RMSSD

instability. In contrast, a lower likelihood of RMSSD instability was associated with putting events into perspective ($r = -.27, p = .036$) and nearly significantly associated with greater use of planning ($r = -.26, p = .050$). No significant associations were observed for the remaining CERQ subscales, any of the EMO-CHECK dimensions, CD-RISC, age, BMI, physical activity, or amount of sleep (all $ps > .064$). Given the exploratory nature of the analyses and the relatively large number of statistical tests conducted, corrections for multiple comparisons were applied. Following false discovery rate (FDR) correction, only the association between catastrophizing and RMSSD instability remained statistically significant ($r = .42, p_{\text{FDR}} = .023$).

Table 3

Point-biserial correlations between RMSSD instability during slow breathing and emotion regulation, resilience, and lifestyle variables.

CERQ	<i>r</i>	<i>p</i>	<i>p</i>_{FDR}
Self-blame	– .20	.128	.294
Other-blame	.26	.047	.288
Rumination	– .11	.412	.526
Catastrophizing	.42	.001	.023
Positive refocusing	.05	.721	.786
Planning	– .26	.050	.288
Positive reappraisal	– .22	.095	.289
Putting into perspective	– .27	.036	.288
Acceptance	– .24	.064	.289
EMO-CHECK			
Awareness	– .21	.113	.289
Sensations	– .14	.291	.478
Clarity	– .16	.238	.421
Understanding	– .04	.759	.786
Acceptance	– .06	.631	.726
Tolerance	– .13	.324	.497
Confrontation	– .12	.363	.522
Self-support	– .17	.199	.381
Modification	– .11	.400	.526
CD-RISC	– .22	.099	.289
Age	– .04	.786	.786
BMI	.07	.599	.725
Physical activity	.21	.106	.288

Note. Positive correlations indicate that higher scores were associated with a greater likelihood of RMSSD instability (1 = unstable), whereas negative correlations indicate that higher scores were associated with a greater likelihood of RMSSD stability (0 = stable).

<i>CERQ</i>	<i>r</i>	<i>p</i>	<i>P_{FDR}</i>
<i>Sleep</i>	.19	.151	.316
<i>Note.</i> Positive correlations indicate that higher scores were associated with a greater likelihood of RMSSD instability (1 = unstable), whereas negative correlations indicate that higher scores were associated with a greater likelihood of RMSSD stability (0 = stable).			

In addition, associations between RMSSD instability and categorical demographic and lifestyle variables were examined. Fisher's exact test indicated no significant association between gender and RMSSD instability ($p = .643$). Similarly, a Chi-square test revealed no significant association between engagement in breathing exercises in daily life and RMSSD instability ($\chi^2(1, N = 59) = 0.09, p = .764$).²

4. DISCUSSION

The present study was conducted to address an important gap in the slow breathing literature. Although previous research has consistently demonstrated that slow breathing increases HRV, considerably less attention has been paid to whether individuals are able to maintain a regulated physiological state throughout a breathing exercise. To address this question, the present study examined changes in RMSSD during a self-paced slow breathing exercise (RQ1), the temporal stability of RMSSD over time (RQ2), and the extent to which RMSSD instability was associated with emotion regulation, resilience, and lifestyle factors (RQ3).

Consistent with previous research, participants exhibited significantly higher HRV values during the slow breathing exercise than during baseline (RQ1). This finding supports a large body of literature demonstrating that slow breathing increases parasympathetic activity and promotes physiological regulation (Laborde et al., 2022; Lehrer et al., 2020; Zaccaro et al., 2018). The observed increase in HRV suggests that participants were generally able to regulate parasympathetic activity through self-paced breathing. Taken together, these findings further support the notion that slow breathing, even without external pacing cues, represents an accessible and effective strategy for promoting physiological regulation. However, achieving a physiological state characterized by enhanced parasympathetic activation does not necessarily imply that this state is maintained consistently throughout the exercise. The temporal stability analyses therefore provide an important extension to previous research by examining whether physiological regulation can be sustained over time.

The most notable finding of the present study emerged when examining the temporal stability of HRV during the breathing exercise (RQ2). Although participants generally exhibited increased HRV levels during self-paced slow breathing, a substantial proportion (i.e., 69%) showed evidence of HRV instability over time. Importantly, HRV instability occurred significantly more often during the self-paced slow breathing phase than during baseline, suggesting that instability was not merely a reflection of naturally occurring fluctuations in cardiac activity. These findings suggest that achieving an average increase in

parasympathetic activity across the sample does not necessarily imply that individuals are able to maintain a regulated state throughout a self-paced breathing exercise. This distinction between achieving and maintaining regulation has received relatively little attention within the breathing literature. Most previous studies have focused on average changes in HRV (Laborde et al., 2022), implicitly assuming that elevated HRV reflects successful regulation throughout the intervention. However, the current findings suggest that comparable average HRV values may conceal important differences in the temporal dynamics of physiological regulation. Some individuals may be able to sustain a relatively stable physiological state, whereas others may alternate between periods of successful regulation and periods of physiological instability. As such, temporal stability may represent an additional, previously overlooked dimension of breathing-based self-regulation.

Although participants were generally able to increase parasympathetic activity, maintaining this regulated physiological state may require sustained attentional control and consistent breathing behavior. Accordingly, temporary fluctuations in attention, motivation, comfort, or breathing consistency may have contributed to the observed instability in RMSSD over time. Alternatively, maintaining a regulated physiological state may itself constitute a self-regulatory challenge, requiring ongoing monitoring and adjustment of breathing behavior. This interpretation is consistent with the findings of RQ3, which showed that individual differences in emotion regulation, specifically catastrophizing, were associated with the likelihood of HRV instability during the breathing exercise. Importantly, this association remained significant after correction for multiple comparisons. Although previous research has primarily focused on associations between emotion regulation and average levels of HRV (e.g. Berna et al., 2014; Bylsma et al., 2024; Mather & Thayer, 2018; Williams et al., 2015), the present findings suggest that emotion regulation may also be relevant for understanding the temporal stability of physiological regulation. Consistent with this interpretation, lower resting HRV has been linked to greater emotion regulation difficulties (Williams et al., 2015), while individuals with poorer emotion regulation show less efficient vagal recovery following emotional challenges (Berna et al., 2014). Our findings suggest that catastrophizing, defined as a cognitive emotion regulation strategy involving the tendency to exaggerate the severity and consequences of negative events (Garnefski et al., 2001), may interfere with an individual's ability to sustain a regulated physiological state during self-paced slow breathing. This interpretation aligns with evidence suggesting that higher HRV reflects greater regulatory resilience (Brown et al., 2021) and is associated with less reliance on maladaptive emotion regulation strategies in daily life (Bylsma et al., 2024). Although several additional associations emerged in theoretically meaningful directions, among which a positive association between instability and blaming others, and a negative association with putting into perspective, these did not survive correction for multiple comparisons and should therefore be interpreted cautiously until replicated in larger samples.

Several strengths of the present study should be acknowledged. A key strength lies in its focus on the temporal stability of physiological regulation. Whereas previous research on slow breathing has primarily focused on average changes in HRV, the current study examined whether participants were able not only to achieve, but also to maintain, a regulated physiological state over time. To capture these temporal dynamics, we employed the OLS-CUSUM procedure, which enabled the identification of within-person

fluctuations and structural changes in HRV that would likely remain undetected when relying solely on average HRV values. By distinguishing between the achievement and maintenance of physiological self-regulation, the present study provides a more nuanced perspective on breathing-based self-regulation and addresses a question that has received relatively little empirical attention. An additional strength is the self-paced design, which increases ecological validity, as participants often practice slow breathing without external pacing cues in daily life. Finally, by combining physiological indicators with self-report measures of emotion regulation, resilience, and lifestyle characteristics, the study adopted a more comprehensive approach to understanding physiological self-regulation. This integrative design allowed us to examine not only whether participants were able to regulate their physiological state, but also whether the maintenance of that regulation was related to individual differences in psychological functioning and lifestyle factors.

The findings of the present study should be interpreted considering several limitations. First, the representativeness of the current sample may limit the broader applicability of the findings. The sample was largely composed of Caucasian women, resulting in restricted demographic variability. Given evidence that HRV and related autonomic processes may differ as a function of demographic characteristics, such as age, sex, and ethnicity (e.g., Hill et al., 2015), future studies should evaluate whether similar patterns of physiological regulation and instability emerge in more diverse populations. Second, although HRV instability was unrelated to prior breathing experience in the current study, participants generally reported limited engagement in breathing practices, averaging fewer than four sessions per week and approximately 37 minutes of practice per week. This is substantially lower than the practice frequency and duration commonly recommended in resonance frequency breathing protocols (Lehrer et al., 2013). Future studies should investigate whether more experienced practitioners exhibit greater physiological stability during breathing exercises and whether long-term practice strengthens the ability to maintain elevated HRV over time. Finally, the analyses examining associations between HRV instability and emotion regulation, resilience, and lifestyle factors were exploratory in nature. Although several associations emerged in theoretically meaningful directions, only the association between catastrophizing and HRV instability remained statistically significant after correction for multiple comparisons. The associations between adaptive emotion regulation strategies, resilience, and HRV stability should therefore be considered preliminary until replicated in larger samples. Moreover, given the cross-sectional design, the directionality of these relationships remains unclear. For instance, habitual emotion regulation strategy use may influence the capacity to sustain physiological self-regulation. Vice versa, difficulties maintaining a regulated physiological state are also likely to affect emotion regulation. Follow-up longitudinal research is needed to clarify this relationship.

5. CONCLUSION

The present study demonstrates that self-paced slow breathing is associated with increased HRV, indicating that individuals are generally able to achieve parasympathetic self-regulation in the absence of external pacing cues. At the same time, a substantial proportion of participants exhibited HRV instability during the breathing exercise, suggesting that achieving physiological self-regulation does not

necessarily imply that it can be maintained over time. Furthermore, higher levels of catastrophizing were associated with a greater likelihood of HRV instability, highlighting a potential role for maladaptive emotion regulation in the maintenance of physiological self-regulation. Overall, the present findings underscore the importance of considering not only whether physiological regulation is achieved, but also whether it can be sustained over time.

Declarations

CONFLICT -OF-INTEREST STATEMENT

The authors declare that they have no conflict of interest.

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Author Contribution

JD, KH, MAV and RDR developed the study concept and contributed to the study design. JD collected the data required for this study. JD and KH performed the data analysis, interpretation, and drafted the paper. KH, MAV and RDR provided critical revisions. All authors approved the final version of the manuscript for submission.

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Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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Footnotes

1. As an additional check, to assess whether RMSSD instability was related to the use of other self-regulation techniques during the slow breathing task, a Fisher's exact test was conducted. No significant association was observed between the use of such techniques and RMSSD instability ($p = .767$). Thus, there was no evidence that participants classified as unstable were more or less likely to rely on additional regulation strategies during the slow breathing task.
2. To examine whether the catastrophizing – instability association was specific to physiological self-regulation (i.e., self-paced slow breathing task) rather than reflecting a general trait-level pattern, these analyses were repeated using baseline RMSSD instability instead. One small association emerged between baseline instability and the EMO-CHECK Sensations subscale ($r = -.33, p = .011$). However, this effect did not survive correction for multiple comparisons. No other significant associations were observed between baseline RMSSD instability and indices of emotion regulation, resilience, lifestyle-, or demographic variables (Supplemental Table 1).

Figures

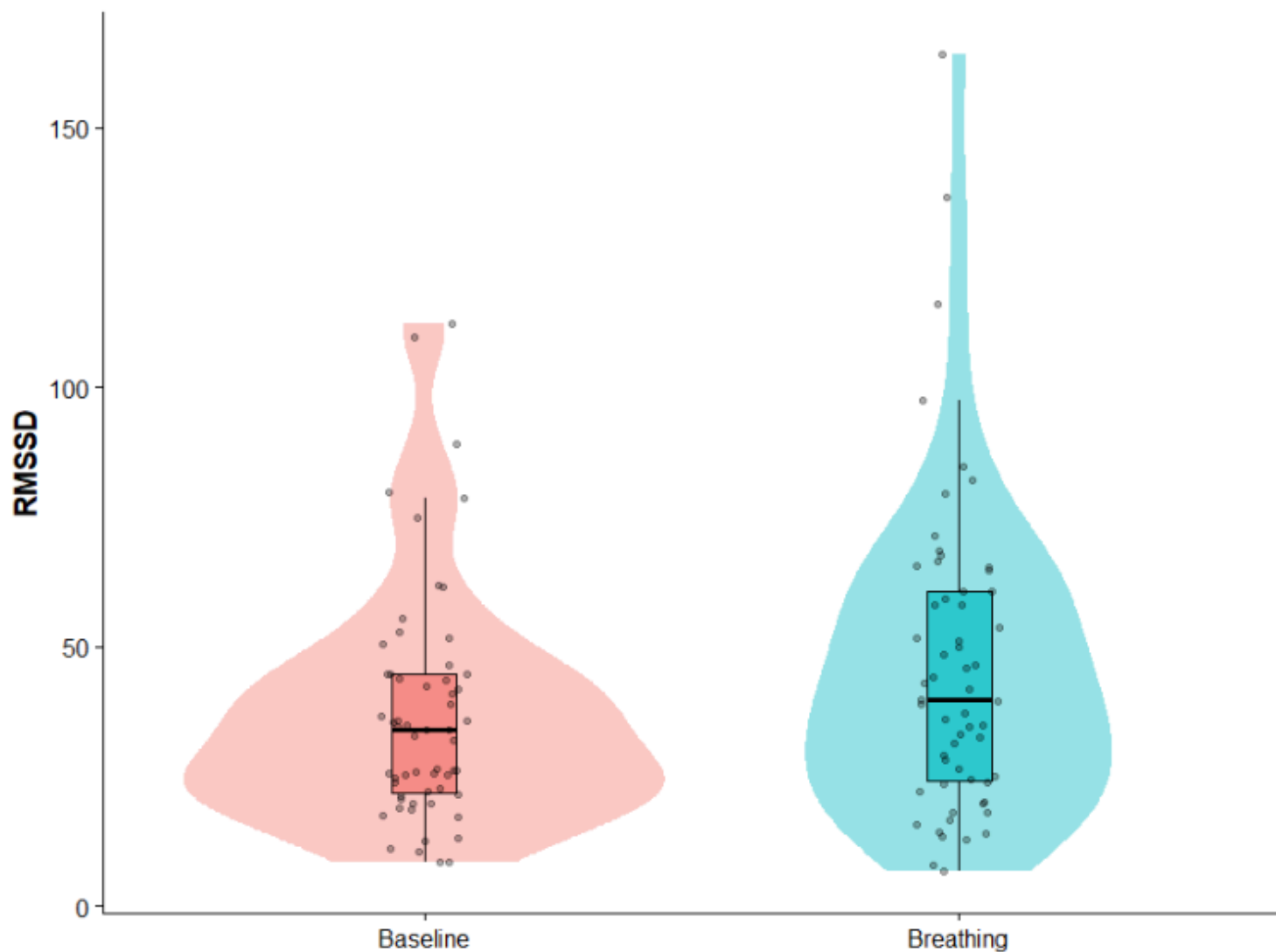


Figure 1

RMSSD values during the baseline and slow breathing phase

Note. During baseline, RMSSD values were $M = 37.21$ ($SD = 22.77$), $Mdn = 33.89$ ($IQR = 22.78$). During the self-paced slow breathing phase, RMSSD values were $M = 46.48$ ($SD = 30.62$), $Mdn = 39.69$ ($IQR = 36.57$).

Supplementary Files

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