Triggered by the Heart: Effectiveness of Two Brief Just in Time Adaptive Interventions (JITAI) for Reducing Stress and Stabilizing Cardiac Autonomic Function

Andreas Richard Schwerdtfeger, Martin Josef Tatschl, Christian Rominger

Submitted to: Journal of Medical Internet Research
on: December 03, 2024

Table of Contents

Triggered by the Heart: Effectiveness of Two Brief Just in Time Adaptive Interventions (JITAI) for Reducing Stress and Stabilizing Cardiac Autonomic Function

Andreas Richard Schwerdtfeger[1] DPhil; Martin Josef Tatschl[1] MSc; Christian Rominger[1] Dr rer nat

[1]University of Graz Graz AT

Corresponding Author:
Andreas Richard Schwerdtfeger DPhil
University of Graz
Universitaetsplatz 2/III
Graz
AT

Abstract

Background: Transient heart rate variability decreases independent of bodily movement (additional heart rate variability reductions; AddHRVr) potentially reflect moments of psychophysiological vulnerability.

Objective: We applied this measure by means of wearables in everyday life to trigger low-threshold 1-min interventions with the aim to stabilize autonomic function and relieve perceived stress and ruminative thoughts.

Methods: In two pre-registered micro-randomized trials participants underwent a 1-day calibration period to derive individualized trigger settings, and then received AddHRVr-triggered and random prompts throughout the following 3 days asking for perceived stress and rumination. In Study 1, N = 60 participants underwent a slow breathing intervention (0.1 Hz resonance breathing) following each prompt and in Study 2, N = 49 participants were micro-randomized to an external attention and mindful breathing intervention, respectively.

Results: Following interventions in both studies, perceived stress and ruminative thoughts significantly declined irrespective of the kind of prompt and intervention. AddHRVr-triggered prompts resulted in a stronger increase in HRV during the slow-paced breathing and mindful breathing interventions and elevated HRV in a time frame of 10 minutes following the interventions (in contrast to random prompts).

Conclusions: Both studies show for the very first time that an AddHRVr algorithm can be used to trigger brief just in time interventions by wearables to stabilize autonomic function, thus potentially promoting cardiac health.

(JMIR Preprints 03/12/2024:69582)
DOI: https://doi.org/10.2196/preprints.69582

Original Manuscript

Running Head: JITAIs triggered by HRV

Triggered by the Heart:

Effectiveness of Two Brief Just in Time Adaptive Interventions (JITAI) for Reducing Stress and Stabilizing Cardiac Autonomic Function

Andreas R. Schwerdtfeger*, Josef M. Tatschl, & Christian Rominger

Conflict of Interest: The authors declare no conflict of interest.

----
* Corresponding author
Andreas R. Schwerdtfeger
Institute of Psychology
Universitaetsplatz 2/III
University of Graz, Graz, Austria
Email: andreas.schwerdtfeger@uni-graz.at
ORCID: 0000-0002-0371-3730

Abstract

Background

Transient heart rate variability decreases independent of bodily movement (additional heart rate variability reductions; AddHRVr) potentially reflect moments of psychophysiological vulnerability.

Objective

We applied this measure by means of wearables in everyday life to trigger low-threshold 1-min interventions with the aim to stabilize autonomic function and relieve perceived stress and ruminative thoughts.

Methods

In two pre-registered micro-randomized trials participants underwent a 1-day calibration period to derive individualized trigger settings, and then received AddHRVr-triggered and random prompts throughout the following 3 days asking for perceived stress and rumination. In Study 1, N = 60 participants underwent a slow breathing intervention (0.1 Hz resonance breathing) following each prompt and in Study 2, N = 49 participants were micro-randomized to an external attention and mindful breathing intervention, respectively.

Results

Following interventions in both studies, perceived stress and ruminative thoughts significantly declined irrespective of the kind of prompt and intervention. AddHRVr-triggered prompts resulted in a stronger increase in HRV during the slow-paced breathing and mindful breathing interventions and elevated HRV in a time frame of 10 minutes following the interventions (in contrast to random prompts).

Conclusions

Both studies show for the very first time that an AddHRVr algorithm can be used to trigger brief just in time interventions by wearables to stabilize autonomic function, thus potentially promoting cardiac health.

Keywords: Cardiac vagal regulation; JITAI; Micro-randomized trial; Resonance breathing; Mindful

breathing

Introduction

Life is not always sunny and we experience various negative feelings like stress, anxiety and ruminative thoughts. These subtle, yet accumulative feelings and thoughts could significantly affect long-term wellbeing and health outcomes [1,2]. Thus, unobtrusively detecting such episodes in daily life and applying low threshold brief interventions in the moment of highest need (i.e., just in time adaptive-interventions, JITAIs [3,4]) could prove a highly effective treatment and prevention strategy for an increasingly stressful life. Contrary to so-called "pull"-interventions necessitating an individual's motivation to request an intervention when needed, "push"-interventions aim to automatically identify moments of highest need (e.g., via wearables) and deliver the appropriate intervention [5]. Thus, the aim of this research was to validate JITAIs designed to reduce stress and perseverative cognition (ruminative thoughts) by leveraging transient non-metabolic decreases in cardiac vagal regulation (so-called additional heart rate variability reductions; AddHRVr [6,7]).

HRV could constitute a particularly sensitive tool to identify such episodes of psychophysiological vulnerability, because it signifies a complex interplay between the autonomic nervous system and the central nervous system [8-10]. Specifically, the vagus nerve as the primary parasympathetic nerve and major constituent of HRV ensures a rapid communication between the brain and the heart (~ 200 ms) with afferent fibers (from the heart to the brain) outweighing efferent fibers (from the brain to the heart). Hence, vmHRV could signal cognitive function, emotion regulation, and states of stress and psychophysiological vulnerability, among others [9,11,12]. Thus, analyzing the rhythm of the heart throughout everyday life situations may inform about the beneficial or compromised psychosocial functioning of an organism in an ever-changing environment. Without the need for excessive time-consuming and burdensome self-reports of perceived stress, letting autonomic regulation decide about the right moment of potential need, the studies in this report aimed for a feasible yet efficient tool to inform JITAIs. Hence, non-metabolic HRV reductions (i.e., AddHRVr) were used to trigger a JITAI, addressing both physiological and psychological indices of well-being.

Recently, we proposed a simulation-based approach to determine individualized trigger settings and assess their sensitivity to psychosocial factors using AddHRVr algorithms [13] (see also https://osf.io/fmt5u/). This approach is based on the root mean squares of successive differences (RMSSD) as a measure of vagally sensitive HRV and involves two steps: First, a calibration period aims to derive personalized regression parameters for the algorithm. Specifically, using 1-minute segments of data across a day (12 h), RMSSD is regressed on bodily movement for each individual. The algorithm uses individualized RMSSD thresholds (> 0.5 *SD*) to identify segments with significant RMSSD reduction compared to predicted values. In a next step, such additional (i.e., non-metabolic) HRV reductions (AddHRVr [6,7] are tracked in the following days and a trigger is emitted when a predefined number of AddHRVr occur within a specific time interval [14]). Notably, in our previous simulation study varying the HRV window from 2 to 30 minutes and the corresponding threshold from 1 to 29 minutes, a “13 out of 28”-algorithm had a power of .806 to detect episodes of low social quality interactions, thus suggesting the a superior performance of this trigger setting [13]. Hence, we used this algorithm setting to trigger JITAIs in two independent studies.

Study 1: Slow paced breathing at 0.1 Hz

In Study 1 we aimed to use an easy to implement brief intervention, which most people can perform quite unobtrusively in various contexts in everyday life. Specifically, slow-paced breathing (0.1 Hz resonance breathing) has been suggested as a powerful and easy to learn technique to improve both mental and physical functions [15-19]. In particular, resonance breathing has a direct effect on autonomic regulation via strengthening vagal efference and stimulating the baroreceptor reflex, which also positively affects higher central nervous system functioning [9,18]. In previous research, we evaluated acute and chronic psychophysiological effects of slow paced breathing interventions and could show beneficial effects on both psychological and physiological function [9,20-22]. Other research reported a reduction in anxiety and perceived stress following 0.1 Hz breathing [18,23], although experimental research could not confirm significant effects for acute stress reactivity [24]. Beneficial effects of slow paced breathing have also been reported for individuals with hypertension and cardiovascular disorders, thus confirming its clinical usefulness [25,26]. Taken together, slow-paced breathing could benefit both autonomic regulation and psychological health. It is an easy to learn intervention that can be applied unobtrusively in various daily life contexts (e.g., during work, leisure time or while being on the way) and can be easily implemented on the smartphone [27].

Aims and hypotheses

The aim of Study 1 was to examine whether a 0.1 Hz breathing JITAI would be particularly beneficial when autonomic function is compromised as indexed by AddHRVr. We used a micro-randomized trial to compare the effectiveness of AddHRVr-triggered and randomly triggered interventions. Precisely, participants in this pre-registered study [28] breathing exercises of 1 minute following a prompt on their smartphone. We hypothesized that perceived stress and ruminative thoughts would diminish more strongly after AddHRVr (vs. random) triggered interventions and that HRV (specifically, RMSSD) would increase more strongly during and following the AddHRVr-triggered slow-paced breathing intervention as compared to random prompts.

Methods

Participants

Overall, 69 individuals participated in the EMA for 3 consecutive days following a 12h-calibration period. Data loss due to excessive ECG-artefacts (n = 7) or positive slopes during the calibration period (n = 1), resulted in a final sample of 61 participants (45 women; 12 men; 0 diverse/ non-binary/other). They had a mean age of 22.88 years (*SD* = 4.56) and a mean body mass index (BMI) of 21.83 kg/m^2 (*SD* = 3.30). The majority of the sample were students (n = 48; 84%), non-smokers (n = 45; 79%) and reported regular physical exercise (n = 30; 53%). Information about race, ethnicity or socioeconomic status were not gathered. The study was approved by the local ethics committee (GZ. 39/93/63 ex 2022/23) and pre-registered via OSF [28]. A power analysis was conducted a priori based on simulation studies [29], focusing on direct within-person effects of small to medium size (assuming a medium-sized ICC and ~30 prompts per participant). The resulting sample size was 60 participants.

Study Design

The study followed a micro-randomized design [30,31] triggering a brief intervention either by episodes of psychophysiological vulnerability (AddHRVr-trigger) or at random times. The design is outlined in Figure 1.

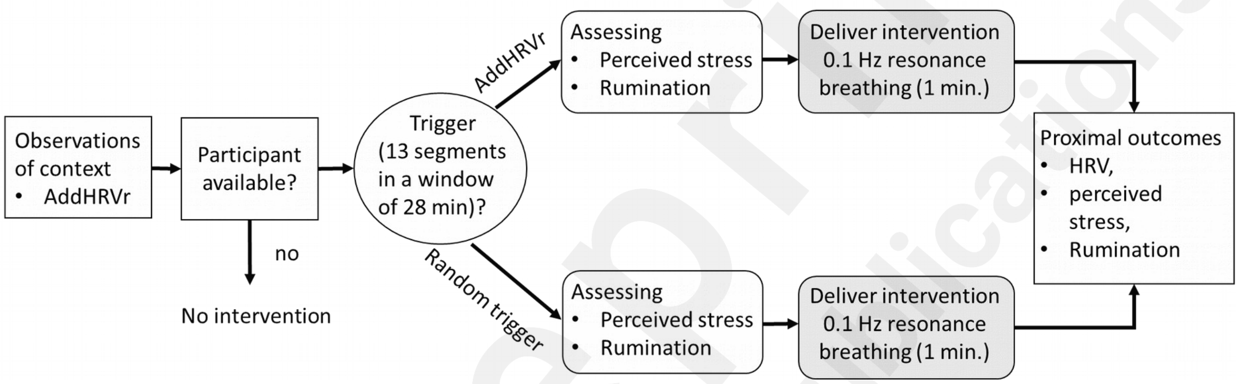

Fig. 1. Schematic illustration of the procedure of Study 1. A slow-paced breathing intervention (0.1 Hz) was either triggered at random points in time or contingent to additional (i.e., non-metabolic) heart rate variability reductions (AddHRVr).

Variables and Instruments

Perceived Stress

Perceived stress was assessed via four items adapted from the Perceived Stress Scale [32,33]. The following items were rated on a 5-point Likert scale between 1 (not at all) and 5 (very much): 'Do you feel that you can cope with things?' (reverse coded), 'Do you feel that you're on top of things?' (reverse coded), 'Do you feel you have control over things?' (reverse coded), 'Do you feel nervous or stressed?' Items were aggregated for each prompt. Of note, the scale showed excellent between-person reliability (pre intervention: R_{KRn} = .98, post intervention: R_{KRn} = .99) and satisfactory within-person reliability (pre intervention: R_{Cn} = .68, post intervention: R_{Cn} = .69) as assessed via generalizability theory analysis [34] applying the package psych in R [35]. The mean average score across individuals and occasions was *M* = 2.23 (*SD* = 0.79) at pre assessment and *M* = 2.11 (*SD* = 0.76) at post assessment with an intraindividual range from 1 to 5.

Rumination

Ruminative thoughts were assessed via a single item measure. In particular, following previous research [36], ruminative thoughts were defined as "When you worry or are ruminating about something over a period of time. It is a summary term for processes such as worrying, brooding, stuck on something, annoyed or grumbling about a problem, or brooding angrily, etc. So, it is a chain of negative thoughts that is difficult to let go of." Answers are given on a five-point Likert scale (from 1 = not at all to 5 = very strongly). The mean average score across individuals was *M* = 2.14 (*SD* = 1.02) at pre assessment and *M* = 2.02 (*SD* = 0.97) at post assessment with an intraindividual range between 1 and 5.

AddHRVr

We applied the EcgMove4-device (movisens GmbH, Karlsruhe, Germany) to record the ECG (with 1,024 Hz), bodily movement and body position (by means of a 3d-accelerosensor, 64 Hz), and air pressure (8 Hz) for 4 weekdays (9 am to 9 pm; except nighttime). The first day (12h; on Monday) served as a calibration day to determine the individual regression parameters between RMSSD and bodily movement for each individual (intercept, slope, and *SD* of RMSSD; for an overview see Table 1). Validation of RMSSD (analyzed for each minute) was verified by an inbuild algorithm. In case of severe artefacts, the 1-minute segment was set to missing. Individuals exhibiting positive slopes were excluded from analysis (n=1). The regression parameters were then used to detect AddHRVr (13 out of 28) and emit a trigger in the subsequent 3 days (from Wednesday to Friday [14]) to initiate smartphone prompts. AddHRVr-triggers were complemented by random triggers. For AddHRV-triggers we applied a silent setting of 60 minutes, meaning that one AddHRVr trigger was emitted per hour at maximum.

Table 1. AddHRVr algorithm calibration parameters derived from 12h baseline recording in Study 1 and Study 2.

	M	*SD*	*Max*	*Min*
Intercept				
Study 1	47.55	18.98	101.66	20.87
Study 2	46.94	22.29	121.87	10.72
Slope				
Study 1	-144.92	100.67	-14.26	-478.38
Study 2	-125.23	79.75	-15.64	-344.55
½ *SD* (RMSSD)				
Study 1	9.70	4.66	23.79	3.97
Study 1	9.54	5.06	28.40	2.94
RMSSD				
Study 1	40.62	16.12	92.81	19.08
Study 2	39.73	17.60	94.74	10.03
Acceleration (g)				
Study 1	0.052	0.018	0.097	0.025
Study 2	0.054	0.018	0.108	0.017

METs

METs were derived from the EcgMove4-sensor, which records acceleration (in g) via a triaxial accelerometer and air pressure. The movisens DataAnalyser software calculates the METs in two steps. First, the activity class is estimated based on acceleration and barometric signals. Second, based on the detected activity class (i.e., sitting, walking, etc.) the algorithm chose the corresponding model for MET estimations, which takes the acceleration metric, the barometric data, and personal parameters (i.e., age, gender, weight, height) into account.

Slow-paced Breathing Intervention (0.1 Hz)

Following each EMA (random and AddHRVr triggered), participants were instructed to breathe slowly for 1-minute via a guided app (Fig. 2). Inhalation was set to 4 seconds and exhalation to 6 seconds, thus arriving at a breathing frequency of 6 breaths per minute (0.1 Hz [9,18,22]. For exploratory purposes, the breathing intervention was partially complemented by hand muscle contractions during inhalation and relaxation during exhalation. However, further analysis confirmed that both intervention types did not result in different HRV patterns (data available upon request), thus we abstained from controlling hand contractions in analyses.

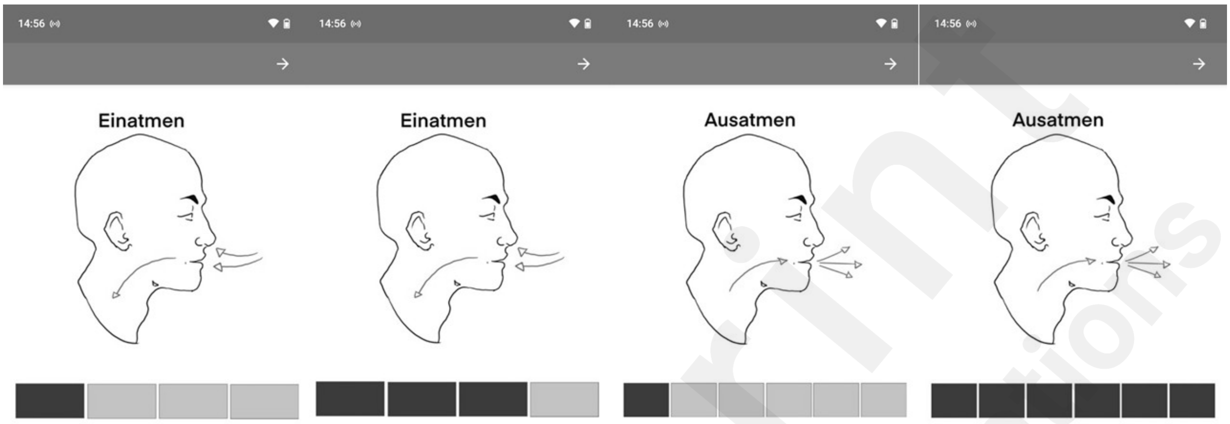

Fig. 2. App-based 0.1 Hz breathing intervention. Inhalation ("Einatmen") was paced for 4 seconds and exhalation ("Ausatmen") for 6 seconds as guided by a progress bar.

Pre-registration and deviation thereof

Some deviations from the pre-registered protocol need to be outlined. First, we specified to assess weight to height ratio in addition to BMI. For reasons of time economy, we focused on BMI and are confident to have captured tendencies of overweight reasonably well. Notably, we specified in the pre-registration to control for smoking, age, gender, and body mass index (BMI). However, since all these covariates turned out to be non-significant and in order to avoid over-specification of the model, we did not include all these variables in the final model, but focused on concurrent smoking and METs when analyzing HRV variables. Second, we did not specify the HRV measure in the pre-registration. However, as outlined in previous research on AddHRVr [6,7,13], RMSSD is considered a core measure of this approach. Nevertheless, in order to evaluate a broader spectrum of HRV trajectories prior to and following the intervention as recommended by some authors [37], we additionally analyzed SDNN and HF-HRV (0.15 - 0.40 Hz) to avoid selective reporting of HRV measures.

Data Parametrization and Statistical Analysis

On average, participants received 45 prompts (*SD* = 8.38), of which 69% were answered, 4% were dismissed, 19% were ignored and 8% incomplete. Noteworthy, 32% of the sample received AddHRVr-triggers, while 68% did not. On average, *M* = 4.14 (*SD* = 7.10) AddHRVr-triggers were emitted with an interindividual range between 0 and 26. To evaluate the effectiveness of the breathing intervention, we applied multilevel models predicting perceived stress, rumination and RMSSD, respectively, by AddHRVr trigger (vs. random trigger) and time (pre vs. post intervention). In order to allow within-person interpretations of the effectiveness of the trigger, this variable was centered within persons [[38]]. The interaction between prompt (random vs. AddHRVr) and time (pre vs. post intervention) would indicate the effectiveness of the AddHRVr-triggered intervention. For RMSSD, quantified as the mean of the 10 minutes prior to each prompt, we deemed it necessary to adjust for METs as a covariate (mean of 10 minutes), since the breathing intervention could, in principle, be performed in any body position and independent of bodily movement (e.g., during walking or standing/sitting still). We analyzed HRV in a time frame of 10 minutes prior to the intervention, during the breathing intervention and the following 10 minutes. Of note, in order to evaluate effects during the intervention, we applied a time frame of ± 2 minutes to account for potential inaccuracy of timing between smartphones and EcgMove4-devices.

We used RMSSD as the core variable of HRV because it has been particularly recommended in previous ambulatory research [[39]] and represents the most often studied ambulatory marker of vagally-mediated HRV [[40]-[42]]. Nonetheless, in order to evaluate the robustness of intervention effects on HRV, we also analyzed HF-HRV and SDNN [[37]]. Specifically, we analyzed HF-HRV as a frequency-domain indicator of vagally-sensitive HRV and SDNN as an indicator of overall autonomic regulation of cardiac activity. HRV measures were logarithmized prior to analysis to account for skewness. We fixed the level of significance at $p < .05$ (two-tailed).

Results

In a first step, we were interested to evaluate whether the slow-paced breathing interventions were performed equally for both trigger conditions. Therefore, we analyzed LF-HRV before and during the breathing exercises via multilevel modeling. It should be noted in this respect that respiratory sinus arrhythmia (i.e., the fluctuation of heart rate concordant with breathing) shifts to the LF-band (0.04 – 0.15 Hz) during breathing with 6 breaths per minute (corresponding to 0.1 Hz) [18]. Precisely, we predicted logarithmized LF-power by the interaction of time (10 minutes prior the intervention coded as -1 vs. 2 minutes around the intervention coded as 0) and trigger (AddHRVr-trigger vs. random trigger). Momentary smoking and METs served as covariates. The interaction was not significant (b = 0.06, p = .325), thus suggesting that the slow-paced breathing exercises were not differently performed between the two types of triggers (AddHRVr-trigger vs. random trigger).

Perceived stress and rumination

Next, we analyzed a model predicting both perceived stress and ruminative thoughts by trigger type (AddHRVr vs. random) and time (pre vs. post intervention). It turned out that both variables significantly declined from pre to post intervention (perceived stress: b = -.12, p < .001; ruminative thoughts: b = -.11, p < .001), but there were no significant interactions between trigger and time, neither for perceived stress (b = 0.02, p = .825) nor rumination (b = -0.06, p = .545).

HRV

First, we analyzed whether RMSSD differed in the course of the intervention between trigger conditions. Therefore, lnRMSSD was averaged in a time window of 10 minutes prior to the intervention, around the 2-minutes of intervention and 10 minutes thereafter. METs and concurrent smoking were treated as covariates in this model to account for metabolic adjustments. Findings are depicted in Table 2.

Table 2. Multilevel regression predicting logarithmized RMSSD before, during and after the slow

paced breathing intervention.

	lnRMSSD		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	3.53	3.44 – 3.62	**<.001**
Metabolic equivalents (METs)	-0.35	-0.36 – -0.35	**<.001**
Smoking (no vs. yes)	-0.03	-0.06 – -0.00	**.028**
Trigger (0 = random vs. 1 = AddHRVr)	-0.35	-0.38 – -0.32	**<.001**
pre vs. intervention [breathing]	0.17	0.16 – 0.19	**<.001**
pre vs. post breathing	0.03	0.02 – 0.04	**<.001**
Trigger × pre vs. intervention [breathing]	0.08	0.02 – 0.14	**.015**
Trigger × pre vs. post breathing	0.12	0.07 – 0.16	**<.001**
Random Effects			
σ^2	0.23		
$\tau_{00\ \text{participant}}$	0.13		
ICC	.35		
$N_{\text{participant}}$	60		
Observations	33758		
Marginal R^2 / Conditional R^2	0.162 / 0.457		

According to expectations, the increase in lnRMSSD during the intervention was significantly stronger following an AddHRVr-trigger as compared to a random trigger (b = 0.08; p = .015). Most importantly, lnRMSSD remained significantly higher 10 minutes after the intervention in the AddHRVr-trigger condition as compared to the random trigger condition (b = 0.12; p < .001). Furthermore, increasing METs and concurrent smoking were accompanied by significantly lower lnRMSSD. The RMSSD-trajectories for both trigger conditions are visualized in Figure 3 (note that we use unadjusted raw scores here to allow for evaluating the plausibility of the data).

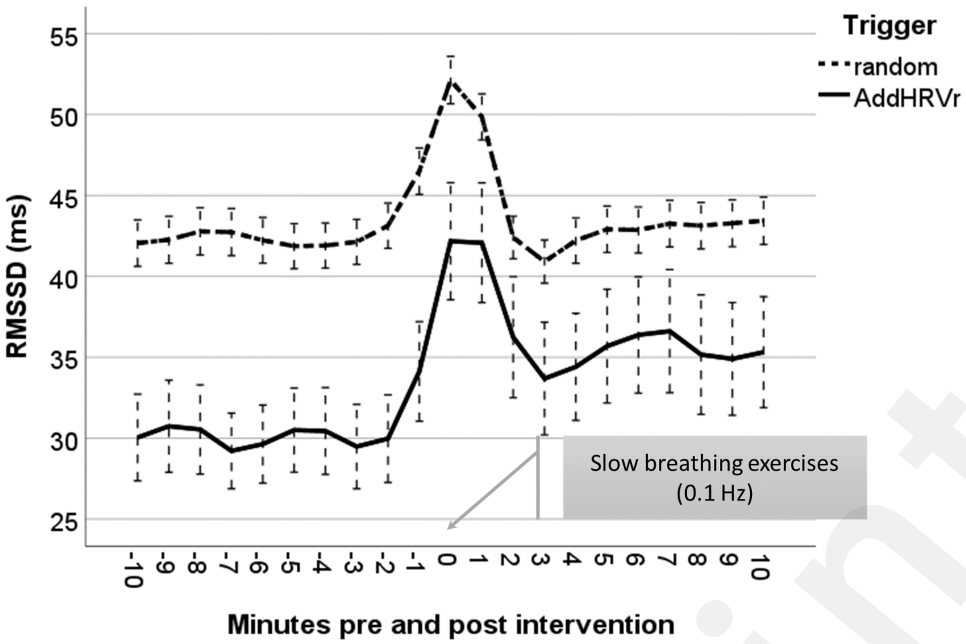

Fig. 3. Trajectories of vagally-mediated HRV (root mean squares of successive differences; RMSSD) 10 minutes before and after the prompt, respectively. The upper stippled line represents RMSSD following random prompts and the lower solid line indicates RMSSD following an AddHRVr-trigger. Stippled lines indicate 95% confidence intervals.

Sensitivity analysis

In order to evaluate the sensitivity of the HRV-increasing effect of the slow-paced breathing intervention, we analyzed alternative indicators of HRV (HF-HRV, SDNN). Notably, the HRV-enhancing effect of the slow breathing intervention to an AddHRVr-trigger relative to a random prompt was also significant for lnHF-HRV (during intervention: b = 0.16, p = .014; post intervention: b = 0.21, p < .001) as well as lnSDNN (during intervention: b = 0.05, p = .067; post intervention (b = 0.06, p < .001), thus suggesting effectiveness of the JITAI on HRV.

Evaluating spontaneous recovery of HRV

In a final step, we aimed to evaluate whether the increase of HRV (i.e., RMSSD) following the intervention is specific to the intervention or more strongly reflects a spontaneous rebound effect. Of note, when non-metabolic HRV is lower during a longer period of time, an increase to normal levels irrespective of any intervention could be expected. Hence, we scanned the dataset for potential

AddHRVr-triggers that were not evoked (e.g., because the silence period prevented an additional prompt). We then calculated the interaction between (virtual) AddHRVr-triggers without any prompt and regular AddHRVr-triggers with intervention. The interaction effect was highly significant (b = 0.08, $p < .001$), indicating that RMSSD increased more strongly at post intervention (relative to pre-intervention) than without any prompted intervention.

Discussion

The aim of this study was to evaluate the effectiveness of physiologically triggered (i.e., AddHRVr) JITAIs to restore psychological well-being and autonomic flexibility. First, findings document that brief 1-minute slow-paced breathing interventions resulted in a general decline of stress and rumination. Second and foremost, slow-paced breathing interventions applied at the moments of compromised cardiac vagal function (i.e., following an AddHRVr-trigger) resulted in a stronger (re-) increase of HRV. Precisely, we observed higher HRV during breathing and up to 10 minutes thereafter, if the intervention was triggered by AddHRVr as compared to randomly triggered prompts. Thus, the latter finding suggests that applying a 1-minute slow-paced breathing intervention could stabilize cardiac autonomic regulation when applied in the moments of lower HRV. The findings of Study 1 generally align with research suggesting beneficial effects of slow breathing on emotional valence, perceived stress and anxiety in controlled settings [[16],[43],[44]].

Importantly, the cardiac autonomic signatures differed significantly between AddHRVr and random prompts. Specifically, just in time slow-paced breathing interventions indeed seemed to be more effective than the very same interventions applied at random times, thus justifying the concept of JITAIs. Interestingly, research could show that a slow breathing biofeedback increased attentional control in individuals reporting higher levels of stress [[45]], thus suggesting that slow breathing exercises are particularly useful when applied during elevated (physiological) stress. It should be noted that AddHRVr contingent increases in HRV during and after breathing could be verified for different indices of HRV (namely RMSSD, HF-HRV and SDNN). Importantly, we also found that the increase in HRV following the AddHRVr-triggered intervention was significantly more pronounced than the natural increase of HRV following (virtual) AddHRVr-triggers without interventions. Together, these findings suggest that momentary disturbed cardiac autonomic regulation could be successfully detected with an AddHRVr algorithm and restored with a brief 1-minute slow-paced breathing intervention.

Limitations

The study had some limitations that need to be acknowledged. First and foremost, the study failed to show that perceived stress and rumination could be reduced more strongly when triggered by HRV. In fact, irrespective of the trigger, both stress and ruminative thoughts were ameliorated in the course of the intervention. Consequently, unlike HRV, the psychological variables do not strongly argue for a JITAI approach. Certainly, more research is warranted examining the exact circumstances under which participants will benefit more strongly with respect to their well-being. Alternatively, refining the trigger settings to detect psychologically vulnerable periods in time with higher accuracy constitutes an important task for future research [[46]]. Second, there was no control intervention, thus limiting the interpretation of the findings. Thus, we could not rule out the possibility that any kind of alternative activity or disruption of everyday life activities may increase well-being and cardiac autonomic regulation. Relatedly, we cannot rule out that reduced perceived stress and rumination indicated mere order effects or psychological adaptation to the repeated assessment, or even socially desirable responding. In principle, other (cognitive) interventions diverting attention from current situational demands could work as well. Hence, an active control condition seems useful. Third, we need to mention that in order to diversify the intervention, we occasionally added guided muscle contractions during breathing exercises, which might have added noise to the effects. However, analyses of the effects of additional muscle contractions did not verify divergent RMSSD trajectories, thus suggesting that this alteration might not have severely biased the effects. Finally, the reliable functioning of the AddHRVr-trigger could be questioned, since only a comparably small proportion of the sample (32%) experienced AddHRVr-triggers. Thus, more research with other samples is needed, before algorithm settings might be adjusted for higher sensitivity.

Irrespective of the critisism raised above, we found convincing evidence that AddHRVr-triggered JITAIs could benefit psychological and physiological states. In Study 2, we were interested to examine whether brief attention focus exercises are similarly useful for reducing perceived stress, ruminative thoughts and cardiac autonomic regulation. Specifically, we used a micro-randomized design to compare effects of an internal (respiration) focused, mindfulness intervention and an external focus intervention, both either triggered by AddHRVr or randomly. Of note, previous research could show that brief mindfulness (breathing) exercises might be effective in increasing HRV [47-49] and improving well-being via reducing distress and rumination [50,51]. Notably, the design of Study 2 allowed to extend Study 1 by including an active control condition. Thus, we could compare the effects of brief mindfulness breathing exercises with external attention exercises both following either an AddHRVr- or a random trigger. Importantly, Study 2 also aimed to compare intervention effects on HRV with spontaneous rebound effects. We predicted that mindful breathing exercises when triggered by AddHRVr are more effective than external focus interventions with respect to perceived stress, ruminative thoughts and HRV.

Study 2

Participants

A power analysis for micro-randomized trials was conducted using the tool MRT-SS [52,53]. A time frame of 4 days was applied with a power of .80 and a treatment effect of 0.2 with a randomization probability of .40 and the level of significance fixed at p < .05. The expected availability was set to .75 and the proximal treatment effect was set to constant. This resulted in a recommended sample size of N = 30. Decreasing the treatment effect to .15 resulted in a sample size of N = 51. Hence, we strived for a sample size of 50 individuals. The final sample comprised of N = 51 participants, of whom 37 were women and 12 were men. There were no gender-diverse individuals in this sample. Mean age of the sample was 23.33 years (*SD* = 3.94) with the majority of them were students (n = 39). There were 10 smokers (20%) and 65.3% of the sample reported regular physical activity. Mean BMI was 23.20 kg/m^2 (*SD* = 4.60). Information about race, ethnicity or socioeconomic status were not gathered. One participant was excluded due to implausible positive slopes between RMSSD and bodily movement during calibration resulting in a final sample size of N = 50. The study was approved by the local ethics committee (GZ. 39/54/63/ ex 2023/24) and pre-registered via OSF [54].

Design

The study design was comparable to Study 1; however, an active control condition (randomized within individuals) was implemented in addition to mindful breathing exercises (see Fig. 4).

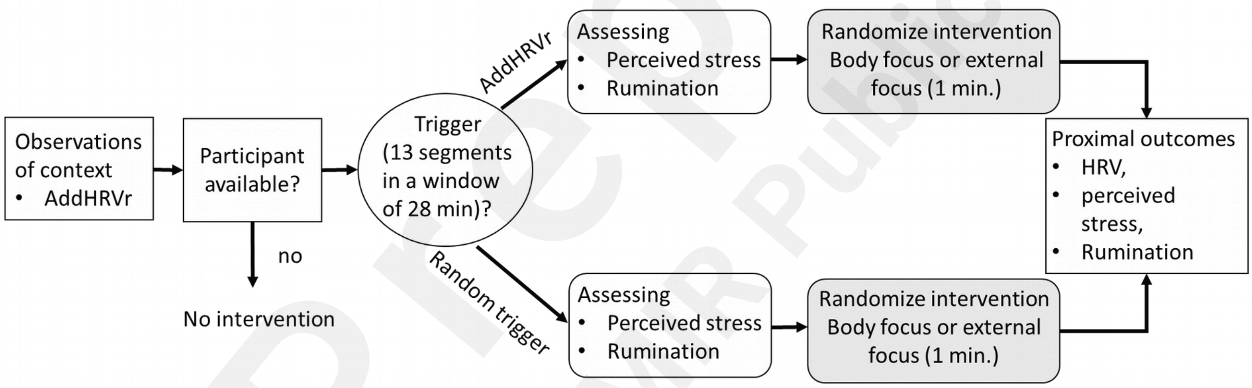

Fig. 4. Schematic illustration of the procedure of Study 2. Two interventions requiring attention either to internal or external cues (see, Fig. 5) were either triggered at random points in time or contingent to additional (i.e., non-metabolic) heart rate variability reductions (AddHRVr).

Following a calibration period of 12h to derive individualized AddHRVr-trigger settings (for descriptive statistics of the calibration period, see Table 1), we applied a (within-person) micro-randomized trial. Participants either received AddHRVr-triggers or random triggers (four random triggers each day). Like in Study 1, there were no restrictions for AddHRVr-triggers, except a silence mode setting of 60 minutes, meaning that following an AddHRVr-trigger, there was a period of 60 minutes without any emitted alarm. Data collection took place on four consecutive days (including the calibration period).

Interventions

We applied brief unobtrusive cognitive exercises (1 minute length), which aimed to direct attention either to the own respiration (mindful breathing) or to a neutral (non-living) object in the outside world. Interventions were presented in random order for each participant. The mindful breathing intervention was informed by research documenting reduced reactivity to repetitive thoughts [[55]] and calming effects on cardiac activity [[47]-[49]]. Considering the external focus exercises, participants were instructed to focus on a neutral, non-living object in their surroundings. The intervention is visualized in Figure 5.

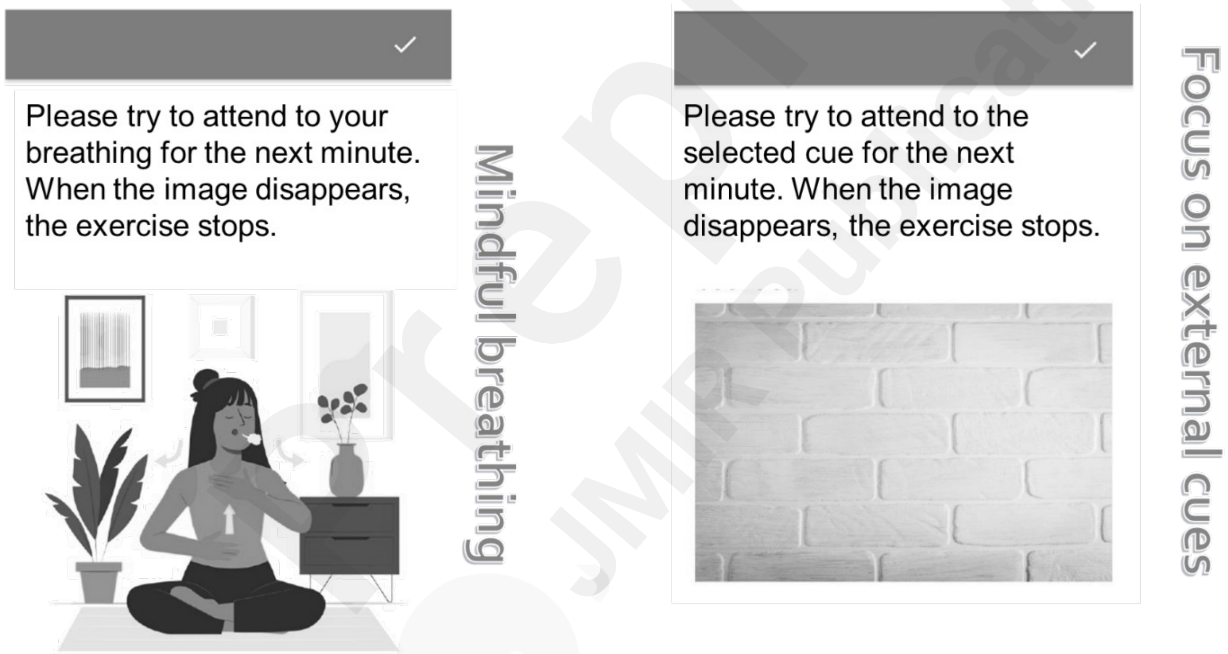

Fig. 5.

Images and brief instructions of the app-based interventions, which were delivered following either AddHRVr- or random triggers. The mindful breathing intervention (left side) asked for directing attention towards mindful breathing, while the external attention task (right side) asked to focus attention toward a neutral object in the environment. Interventions were performed for 1 minute, randomized for trigger type.

Perceived Stress

The same items as in Study 1 were applied. Again, the scale showed excellent between-person reliability (pre intervention: R_{KRn} = .97, post intervention: R_{KRn} = .98) and satisfactory within-person reliability (pre intervention: R_{Cn} = .62, post intervention: R_{Cn} = .65) as assessed via generalizability theory analysis [34] applying the package psych in R [35]. The mean average score across individuals and occasions was *M* = 1.91 (*SD* = 0.84) for pre-assessment and *M* = 1.84 (*SD* = 0.79) for post assessment with an intraindividual range from 1 to 5. Stress scores were lower as compared to Study 1.

Rumination

Ruminative thoughts were assessed with the same item as in Study 1. The mean average score across individuals was *M* = 1.78 (*SD* = 1.03) for pre-assessment and *M* = 1.68 (*SD* = 0.94) for post-assessment with an intraindividual range between 1 and 5. Hence, rumination scores were lower than in Study 1.

Pre-registration and deviation thereof

We pre-registered five hypotheses in this pre-registration [54]. For the purpose of this study, we concentrated on three of them (1. A mindfulness-based breathing intervention leads to a greater increase in HRV after a detected, non-metabolic HRV reduction than a control intervention. 2. A mindfulness-based breathing intervention leads to a greater decrease in subjective stress after a detected, non-metabolic HRV reduction than a control intervention. 3. A mindfulness-based breathing intervention leads to a greater decrease in rumination after a detected, non-metabolic HRV reduction than a control intervention). In order to align this research with Study 1, we did not analyze the impact of the intervention on perceived safety and positive affect.

Data parametrization and statistical analysis

On average, participants received 43 prompts (*SD* = 11.97), of which 60% were answered, 7.5% were dismissed, 29% were ignored and 1% incomplete. Of note, 12% of the sample received no AddHRVr-triggers, while the remaining participants (88%) received between 1 and 39 AddHRVr-triggers. On average, M = 14.41 (SD = 10.72) AddHRVr-triggers were emitted.

Mixed effects modeling was applied throughout. We predicted perceived stress and ruminative thoughts, respectively, by trigger (AddHRVr vs. random), intervention type (respiration focus vs. external focus), time (pre vs. post intervention), and the interaction of all three variables. HRV was predicted by trigger (AddHRVr vs. random), intervention type (respiration focus vs. external focus), time (10 minutes pre intervention coded as -1, 2 minutes window around the intervention coded as 0, 10 minutes post intervention coded as 1), and the interaction of all three variables. Moreover, like in Study 1 we additionally controlled for age, gender, BMI, METs, and momentary smoking. Continuous predictor variables were centered. Moreover, we centered trigger and intervention on the within-person level to allow interpretation of within-person effects [[38]]. For sensitivity analysis, we re-calculated the model, this time predicting HF-HRV and SDNN. The level of significance was fixed at $p < .05$ (two-tailed).

Results

Perceived stress and rumination

Like in Study 1, we found significant effects of time for both perceived stress (b = -0.07, p = .011) and rumination (b = -0.10, p = .002), thus documenting significant decreases in both variables from pre- to post-intervention. No other effects were significant. Specifically, there were no significant interactions between trigger type, intervention type and time for perceived stress (b = -0.03, p = .806) and rumination (b = -0.18, p = .179).

HRV

Analysis of lnRMSSD revealed a significant three-way interaction between trigger, intervention type and pre-vs. intervention phase (b = 0.10, p = .026), thus suggesting that the change from pre to post intervention differed as a function of trigger and intervention type. In order to further qualify this interaction, we rescaled both trigger and intervention type to examine the interaction of the remaining variables. When the external cues intervention type was set to reference, the interaction between trigger and pre vs. intervention phase was not significant (b = -0.007, p = .827), thus suggesting that for the external cues condition the increase in RMSSD from pre-intervention to the intervention phase was not dependent on the type of trigger (Fig. 6, left column). However, for the mindful breathing intervention, this interaction proved significant (b = 0.09, p = .004), thus indicating that when performed following an AddHRVr-trigger, mindful breathing resulted in a significantly larger increase in RMSSD as compared to following a random trigger. This finding is illustrated in Figure 6 (right column). Further analyses indicated that when the random trigger was set to reference, the interaction of intervention type and pre vs. intervention phase was not significant (b = -.01, p = .627; Fig. 6, top lines left and right). Of note, when the AddHRVr-trigger was set to reference, the interaction was significant (b = 0.07, p = .013), thus documenting that when triggered at lower HRV (AddHRVr), the mindful breathing intervention resulted in significantly larger RMSSD increases as compared to the external attention intervention (Fig. 6, bottom lines left and right).

Furthermore, the significant trigger by pre vs. post intervention interaction (b = 0.09, p < .001), which was not further qualified by a three-way interaction involving intervention type, suggests that following and AddHRVr-trigger RMSSD was significantly higher during the post intervention period as compared to when triggered randomly. Hence, any of the interventions performed when HRV was low (AddHRVr) resulted in elevated RMSSD in a time window of 10 minutes post intervention. Finally, it should be noted that like in Study 1, RMSSD was significantly lower with increasing METs and when participants smoked.

Table 3. Multilevel regression predicting logarithmized RMSSD before, during and after both types of triggers and intervention.

	lnRMSSD		
Predictors	*Estimates*	*CI*	*p*
(Intercept)	3.41	3.29 – 3.53	**<.001**

Metabolic equivalents (METs)	-0.22	-0.23 – -0.21	**<.001**
Smoking (no vs. yes)	-0.28	-0.31 – -0.25	**<.001**
Trigger (0 = random vs. 1 = AddHRVr)	-0.35	-0.37 – -0.33	**<.001**
Intervention type (mindful breathing vs. external focus)	-0.02	-0.04 – 0.00	**.047**
pre vs. Intervention	0.08	0.07 – 0.10	**<.001**
pre vs. post intervention	0.04	0.03 – 0.06	**<.001**
Trigger × intervention	-0.07	-0.11 – -0.02	**.003**
Trigger × pre vs. intervention	0.04	-0.00 – 0.08	.054
Trigger × pre vs. post intervention	0.09	0.06 – 0.12	**<.001**
Intervention × pre vs. Intervention	0.03	-0.01 – 0.07	.104
Intervention × pre vs. post intervention	-0.00	-0.03 – 0.03	.931
Trigger × intervention × pre vs. Intervention	0.10	0.01 – 0.18	**.027**
Trigger × intervention × pre vs. post intervention	0.04	-0.02 – 0.10	.230
Random Effects			
σ^2	0.21		
$\tau_{00\ \text{participant}}$	0.19		
ICC	0.47		
$N_{\text{participant}}$	50		
Observations	20418		
Marginal R^2 / Conditional R^2	0.127 / 0.534		

For illustration purposes, Figure 6 depicts the trajectories of RMSSD (raw values) unadjusted for covariates for each trigger and intervention type.

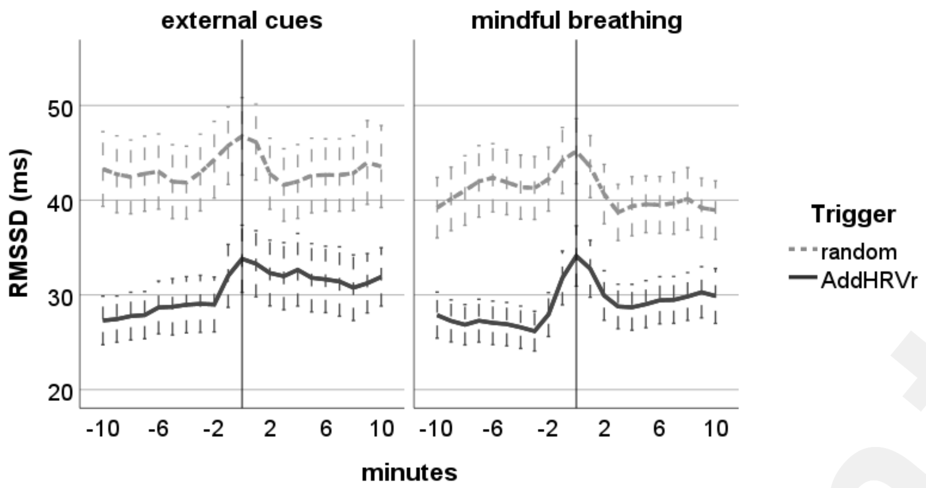
external cues
mindful breathing
RMSSD (ms)
50
40
30
20
-10
-6
-2
2
6
10
minutes
Trigger
random
AddHRVr

Fig. 6. Trajectories of vagally-mediated HRV (root mean squares of successive differences; RMSSD) 10 minutes before and after the prompt, respectively. The upper stippled line represents RMSSD following random prompts and the lower solid line indicates RMSSD following an AddHRVr-trigger. The external attention intervention (external cues) is depicted on the left side and the mindful breathing intervention on the right side. Stippled lines indicate 95% confidence intervals.

Sensitivity analyses

As in Study 1, sensitivity analyses were conducted for both lnHF-HRV and lnSDNN. For lnHF-HRV, the three-way interaction between trigger, intervention type and pre-vs. post intervention phase was significant (b = 0.18, p = .049). The same was evident for lnSDNN (b = 0.08, p = .016), thus replicating the findings for RMSSD. Furthermore, the two-way interaction between trigger and pre vs. post intervention phase could be confirmed for lnHF-HRV (b = 0.17, p < .001) and lnSDNN (b = 0.05, p < .001), respectively. Hence, effects appeared robust for HRV.

Evaluating spontaneous recovery of HRV

Mirroring the approach of Study 1, we finally evaluated whether the increase in HRV after both interventions contingent to an AddHRVr-trigger was higher as compared to spontaneous rebound of HRV following (virtual) AddHRVr-triggers without interventions. The interaction between intervention (AddHRVr-trigger with intervention vs. virtual AddHRVr-trigger without intervention) and time (pre vs. post assessment) was significant (b = 0.07, p < .001), thus documenting that AddHRVr-triggered interventions resulted in a significantly higher increase in RMSSD as compared to AddHRVr-triggers without intervention. Interestingly, the effect size was similar to that of Study 1.

Discussion of Study 2

The aim of Study 2 was to replicate and extend the findings of Study 1. Specifically, applying a micro-randomized trial informed by either AddHRVr or random triggering, we could observe that the mindful breathing intervention resulted in a significantly larger increase of HRV when performed during episodes of reduced HRV (i.e., AddHRVr) as compared to random moments in time. Hence, this finding replicated the result of Study 1 in suggesting a cardiac vagal boost resulting from brief 1-min breathing-focused interventions and thus confirms research on the beneficial effects of mindful breathing for mental health [50,51]. Moreover, we could replicate the significant increase in HRV in a time frame of up to 10 minutes following the intervention. Importantly, this finding was not restricted to the mindful breathing exercise, but was also evident for the external attention intervention. Like in Study 1, this cardiac vagal rebound relative to pre-intervention levels was more pronounced than could normally be expected (without interventions). Thus, it seems that shifting attention to either internal or external cues could restore cardiac vagal function to a certain degree.

Although findings appear promising, we need to emphasize that, like in Study 1, in contrast to the physiological HRV effects the psychological effects for stress and rumination were evident irrespective of the cardiac autonomic state and, moreover, independent of the type of intervention. This result aligns with research suggesting, for example, beneficial psychological effects of breathing exercises irrespective of the pace [56]. Since intervention type had no general impact on psychological variables, common mechanisms inherent in both interventions need to be discussed. First and foremost, it could be assumed that both interventions facilitated distraction from ongoing activities. Distraction has been considered a powerful emotion regulation strategy [57], especially when combined with acceptance [58]. Noteworthy, there is also neurobiological evidence that distraction as an emotion regulation strategy is associated with a comparably strong decrease in amygdala activity, thus substantiating the beneficial effects on subjective well-being [59]. Within a broader perspective, attentional deployment has been considered crucial for emotion regulation, for example, either to distract oneself from negative cues or refocus on positive cues [60]. Taken together, we would assume that the effectiveness of the JITAIs applied in this research was mainly driven by deployment of attention.

General Discussion

To our knowledge, these are the very first micro-randomized trials using an AddHRVr algorithm to automatically identify moments of psychophysiological vulnerability and trigger a JITAI (for a similar approach using physiological data, see [[61]]). Both studies revealed that brief 1-minute interventions in everyday life delivered via a smartphone are feasible and could lead to decreases in perceived stress and ruminative thoughts, thus verifying their potential to increase mental well-being. Furthermore, both studies showed that when triggered during episodes of lower cardiac vagal regulation independent of bodily movement (AddHRVr) either a 1-minute slow paced breathing intervention or a mindful breathing intervention successfully increased HRV to a larger extend than when triggered at random times. This finding is particularly important as it suggests that JITAIs delivered at moments of compromised HRV could immediately boost cardiac vagal function. Importantly, as the analyses of the post intervention phase revealed, any kind of intervention proved successful in restoring HRV up to 10 minutes to a certain degree. Noteworthy, the increase in HRV following the interventions was stronger as could normally be expected when no interventions were conducted. Hence, although the immediate effects of the interventions were rather short-lived, HRV could at least partially be restored and reached a higher level in a time window of 10 minutes following the interventions as observed when no AddHRVr trigger was delivered. It should be noted in this respect that this finding was independent of the type of intervention; hence, even an external focus exercise resulted in a significant increase in HRV from pre to post intervention. It is particularly noteworthy that sensitivity analyses using SDNN and HF-HRV as HRV metrics could largely confirm the immediate and post intervention effects in both studies. Hence, findings were not restricted to a specific metric, but showed evidence towards a generalized increase in cardiac autonomic flexibility, thus suggesting clinical relevance. As mentioned previously, we would suggest that distraction or attentional deployment was responsible for these effects.

Limitations

Several limitations need to be mentioned. First, in Study 1 only about 1/3 of the sample received AddHRVr-triggers, thus suggesting that either the trigger setting was too conservative ultimately missing less severe episodes of cardiac vagal reductions in most participants or calibration was not sensitive enough to identify episodes of psychophysiological vulnerability. The trigger settings deemed more suitable for Study 2 with 88% of the sample experiencing AddHRVr-triggers. We are not sure about the cause of this discrepancy. However, it should be noted in this respect that the performance of the trigger depends on the generalizability of the 12h calibration period. If, for example, during the following days physical activity increases or decreases, algorithm settings could prove non-valid, thus leading to more or less accurate triggers emitted. Future research is advised to aim for a representative day for calibrating the algorithm or to use more adaptive trigger settings, for example, via implementing dynamic algorithms [[46]] adjusting the intercept, which could account for shifts in autonomic regulation towards higher or lower levels of RMSSD. Hence, further research is warranted to develop more sensitive AddHRVr-algorithm settings to trigger JITAIs. Easier to handle algorithms might also allow to scale up the application of JITAIs by means of commercially available wearables. Second, assuming rather medium to large JITAI effects justifying practical applications of such treatments, sample sizes for both studies were rather moderate. Future research should increase both sample sizes and days of assessment to uncover more moderate effects, which could then also test more sensitively the superiority of AddHRVr-triggered interventions for perceived stress and rumination. Third, while we analyzed immediate and delayed cardiac autonomic effects of the JITAIs, it should be kept in mind that the analyzed time window for the post intervention effects was restricted to 10 minutes. It would be worthwhile to analyze longer time scales in order to examine more sustained effects of the 1-minute interventions. Finally, although this research indicated that JITAIs triggered by HRV are promising to intervene at the right moments and have convincing proximal effects, their long-term (distal) impact on physical and psychological well-being is yet unclear and calls for further research regarding their superiority relative to traditional intervention regiments.

Conclusion

The concept of JITAIs has raised considerable interest in recent years and given the formidable growth and availability of wearables, digital mobile technologies and algorithm developments, the field will continue to prosper. In this research, we could show that applying brief slow-paced breathing or mindful breathing interventions in everyday life via smartphones triggered at moments of vulnerability seems to stabilize mental health and cardiac autonomic function up to 10 minutes following the interventions, thus aligning with previous research conducted in traditional, standardized settings [[9],[17],[18],[21],[43],[51]]. Our findings suggest that 1-minute cognitive or behavioral interventions could indeed increase cardiac vagal regulation, especially when applied during compromised autonomic flexibility (e.g., stress). However, research is yet at its infancy and future studies need to convincingly demonstrate that JITAIs are superior to traditional intervention regiments and worth the tremendous effort in setting up algorithms sensitive and specific to certain psychophysiological states (e.g., stress).

Statement of Relevance

Frequent episodes of adverse psychological states, like stress could impact health and well-being in the long run. Identifying such moments of vulnerability could be useful in order to directly counter such states via micro-interventions to ameliorate their health impact. However, the usefulness of such interventions needs solid empirical research. In two studies we could show that short breathing-focused exercises of 1-minute length applied in moments of compromised autonomic flexibility (low non-metabolic heart rate variability) restored well-being and autonomic function. Findings suggest that brief psychological interventions can be implemented in daily life via wearables, possibly benefiting health longitudinally.

References

1. Fang L, Marchetti I, Hoorelbeke K, Koster EHW. Do daily dynamics in rumination and affect predict depressive symptoms and trait rumination? An experience sampling study. *J Behav Ther Exp Psychiatry*. 2019;63:66-72. doi:10.1016/j.jbtep.2018.11.002

2. Wichers M. The dynamic nature of depression: a new micro-level perspective of mental disorder that meets current challenges. *Psychol Med*. 2014;44(7):1349-1360. doi:10.1017/S0033291713001979

3. Nahum-Shani I, Smith SN, Spring BJ, et al. Just-in-Time Adaptive Interventions (JITAIs) in mobile health: Key components and design principles for ongoing health behavior support. *Ann Behav Med*. 2018;52(6):446-462. doi:10.1007/s12160-016-9830-8

4. Wang L, Miller LC. Just-in-the-Moment Adaptive Interventions (JITAI): A meta-analytical review. *Health Commun*. 2020;35(12):1531-1544. doi:10.1080/10410236.2019.1652388

5. Dobson R, Li LL, Garner K, Tane T, McCool J, Whittaker R. The use of sensors to detect anxiety for in-the-moment intervention: Scoping review. *JMIR Ment Health*. 2023;10:e42611. doi:10.2196/42611

6. Brown SBRE, Brosschot JF, Versluis A, Thayer JF, Verkuil B. New methods to optimally detect episodes of non-metabolic heart rate variability reduction as an indicator of psychological stress in everyday life. *Int J Psychophysiol*. 2018;131:30-36. doi:10.1016/j.ijpsycho.2017.10.007

7. Verkuil B, Brosschot JF, Tollenaar MS, Lane RD, Thayer JF. Prolonged non-metabolic heart rate variability reduction as a physiological marker of psychological stress in daily life. *Ann Behav Med*. 2016;50(5):704-714. doi:10.1007/s12160-016-9795-7

8. Thayer JF, Lane RD. Claude Bernard and the heart-brain connection: further elaboration of a model of neurovisceral integration. *Neurosci Biobehav Rev*. 2009;33(2):81-88. doi:10.1016/j.neubiorev.2008.08.004

9. Schwerdtfeger AR, Schwarz G, Pfurtscheller K, Thayer JF, Jarczok MN, Pfurtscheller G. Heart rate variability (HRV): From brain death to resonance breathing at 6 breaths per minute. *Clin Neurophysiol*. 2020;131(3):676-693. doi:10.1016/j.clinph.2019.11.013

10. Pfurtscheller G, Schwerdtfeger AR, Seither-Preisler A, et al. Brain-heart communication: Evidence for "central pacemaker" oscillations with a dominant frequency at 0.1Hz in the cingulum. *Clin Neurophysiol*. 2017;128(1):183-193. doi:10.1016/j.clinph.2016.10.097

11. Appelhans BM, Luecken LJ. Heart rate variability as an index of regulated emotional responding. *Review of General Psychology*. 2006;10(3):229-240. doi:10.1037/1089-2680.10.3.229

12. Shaffer F, McCraty R, Zerr CL. A healthy heart is not a metronome: an integrative review of the heart's anatomy and heart rate variability. *Front Psychol*. 2014;5:1040. doi:10.3389/fpsyg.2014.01040

13. Schwerdtfeger AR, Rominger C. Feelings from the heart: Developing HRV decrease-trigger algorithms via multilevel hyperplane simulation to detect psychosocially meaningful episodes in everyday life. *Psychophysiology*. 2021;58(11):e13914. doi:10.1111/psyp.13914

14. Rominger C, Schwerdtfeger AR. The real-time application of an additional HRV reduction algorithm to detect negative psychosocial states. *Zeitschrift für Psychologie*. 2023;231(4):291-301. doi:10.1027/2151-2604/a000537

15. Aschbacher K, Mather M, Lehrer P, Gevirtz R, Epel E, Peiper NC. Real-time heart rate

variability biofeedback amplitude during a large-scale digital mental health intervention differed by age, gender, and mental and physical health. *Psychophysiology*. 2024;61(6):e14533. doi:10.1111/psyp.14533

16. Laborde S, Allen MS, Borges U, et al. Effects of voluntary slow breathing on heart rate and heart rate variability: A systematic review and a meta-analysis. *Neurosci Biobehav Rev*. 2022;138:104711. doi:10.1016/j.neubiorev.2022.104711

17. Russo MA, Santarelli DM, O'Rourke D. The physiological effects of slow breathing in the healthy human. *Breathe (Sheff)*. 2017;13(4):298-309. doi:10.1183/20734735.009817

18. Sevoz-Couche C, Laborde S. Heart rate variability and slow-paced breathing:when coherence meets resonance. *Neurosci Biobehav Rev*. 2022;135:104576. doi:10.1016/j.neubiorev.2022.104576

19. Shao R, Man ISC, Lee TMC. The effect of slow-paced breathing on cardiovascular and emotion functions: A meta-analysis and systematic review. *Mindfulness*. 2024;15(1):1-18. doi:10.1007/s12671-023-02294-2

20. Rominger C, Graßmann TM, Weber B, Schwerdtfeger AR. Does contingent biofeedback improve cardiac interoception? A preregistered replication of Meyerholz, Irzinger, Withöft, Gerlach, and Pohl (2019) using the heartbeat discrimination task in a randomised control trial. *PLoS One*. 2021;16(3):e0248246. doi:10.1371/journal.pone.0248246

21. Tatschl JM, Hochfellner SM, Schwerdtfeger AR. Implementing mobile HRV biofeedback as adjunctive therapy during inpatient psychiatric rehabilitation facilitates recovery of depressive symptoms and enhances autonomic functioning short-term: A 1-year pre-post-intervention follow-up pilot study. *Front Neurosci*. 2020;14:738. doi:10.3389/fnins.2020.00738

22. Tatschl JM, Schwerdtfeger AR. Squeeze the beat: Enhancing cardiac vagal activity during resonance breathing via coherent pelvic floor recruitment. *Psychophysiology*. 2022;59(12):e14129. doi:10.1111/psyp.14129

23. Schumann A, Helbing N, Rieger K, Suttkus S, Bär K-J. Depressive rumination and heart rate variability: A pilot study on the effect of biofeedback on rumination and its physiological concomitants. *Front Psychiatry*. 2022;13:961294. doi:10.3389/fpsyt.2022.961294

24. Tanzmeister S, Rominger C, Weber B, Tatschl JM, Schwerdtfeger AR. Singing at 0.1 Hz as a resonance frequency intervention to reduce cardiovascular stress reactivity? *Front Psychiatry*. 2022;13:876344. doi:10.3389/fpsyt.2022.876344

25. Joseph CN, Porta C, Casucci G, et al. Slow breathing improves arterial baroreflex sensitivity and decreases blood pressure in essential hypertension. *Hypertension*. 2005;46(4):714-718. doi:10.1161/01.HYP.0000179581.68566.7d

26. Zou Y, Zhao X, Hou Y-Y, et al. Meta-analysis of effects of voluntary slow breathing exercises for control of heart rate and blood pressure in patients with cardiovascular diseases. *Am J Cardiol*. 2017;120(1):148-153. doi:10.1016/j.amjcard.2017.03.247

27. Lin I-M. Effects of a cardiorespiratory synchronization training mobile application on heart rate variability and electroencephalography in healthy adults. *Int J Psychophysiol*. 2018;134:168-177. doi:10.1016/j.ijpsycho.2018.09.005

28. Schwerdtfeger AR, Rominger C, Eipeldauer B. Evaluation of a just in time adaptive intervention (JITAI) using non-metabolic heart rate variability reductions. Published 2023, June 24. Accessed 2024, December 3. https://osf.io/f73g5

29. Arend MG, Schäfer T. Statistical power in two-level models: A tutorial based on Monte Carlo simulation. *Psychol Methods*. 2019;24(1):1-19. doi:10.1037/met0000195

30. Golbus JR, Dempsey W, Jackson EA, Nallamothu BK, Klasnja P. Microrandomized trial design for evaluating just-in-time adaptive interventions through mobile health technologies for cardiovascular disease. *Circ Cardiovasc Qual Outcomes*. 2021;14(2):e006760. doi:10.1161/CIRCOUTCOMES.120.006760

31. Klasnja P, Smith S, Seewald NJ, et al. Efficacy of contextually tailored suggestions for physical activity: A micro-randomized optimization trial of HeartSteps. *Ann Behav Med*. 2019;53(6):573-582. doi:10.1093/abm/kay067

32. Cohen S, Williamson GM. Perceived stress in a probability sample of the United States. In: Spacapan S, Oskamp S, eds. *The social psychology of health*. Sage; 1988:31-67.

33. Reichenberger J, Kuppens P, Liedlgruber M, et al. No haste, more taste: An EMA study of the effects of stress, negative and positive emotions on eating behavior. *Biol Psychol*. 2018;131:54-62. doi:10.1016/j.biopsycho.2016.09.002

34. Brennan RL. *Generalizability Theory*. Springer; 2001.

35. *Psych: Procedures for Psychological, Psychometric, and Personality Research*; 2024. https://doi.org/10.32614/CRAN.package.psych [In Citavi anzeigen].

36. Pieper S, Brosschot JF, van der Leeden R, Thayer JF. Prolonged cardiac effects of momentary assessed stressful events and worry episodes. *Psychol Med*. 2010;72(6):570-577. doi:10.1097/PSY.0b013e3181dbc0e9

37. Laborde S, Mosley E, Thayer JF. Heart rate variability and cardiac vagal tone in psychophysiological research - Recommendations for experiment planning, data analysis, and data reporting. *Front Psychol*. 2017;8:213. doi:10.3389/fpsyg.2017.00213

38. Yaremych HE, Preacher KJ, Hedeker D. Centering categorical predictors in multilevel models: Best practices and interpretation. *Psychol Methods*. 2023;28(3):613-630. doi:10.1037/met0000434

39. Goedhart AD, van der Sluis S, Houtveen JH, Willemsen G, Geus EJC de. Comparison of time and frequency domain measures of RSA in ambulatory recordings. *Psychophysiology*. 2007;44(2):203-215. doi:10.1111/j.1469-8986.2006.00490.x

40. Gerteis AKS, Schwerdtfeger AR. When rumination counts: Perceived social support and heart rate variability in daily life. *Psychophysiology*. 2016;53(7):1034-1043. doi:10.1111/psyp.12652

41. Schwerdtfeger AR, Paul L, Rominger C. Momentary feelings of safety are associated with attenuated cardiac activity in daily life: Preliminary evidence from an ecological momentary assessment study. *Int J Psychophysiol*. 2022;182:231-239. doi:10.1016/j.ijpsycho.2022.10.008

42. Schwerdtfeger AR, Scheel S-M. Self-esteem fluctuations and cardiac vagal control in everyday life. *Int J Psychophysiol*. 2012;83(3):328-335. doi:10.1016/j.ijpsycho.2011.11.016

43. Goessl VC, Curtiss JE, Hofmann SG. The effect of heart rate variability biofeedback training on stress and anxiety: a meta-analysis. *Psychol Med*. 2017;47(15):2578-2586. doi:10.1017/S0033291717001003

44. Magnon V, Dutheil F, Vallet GT. Benefits from one session of deep and slow breathing on vagal tone and anxiety in young and older adults. *Sci Rep*. 2021;11(1):19267. doi:10.1038/s41598-021-98736-9

45. Blaser BL, Weymar M, Wendt J. The effect of a single-session heart rate variability biofeedback on attentional control: does stress matter? *Front Psychol*. 2023;14:1292983. doi:10.3389/fpsyg.2023.1292983

46. Rominger C, Schwerdtfeger AR. Feelings from the heart Part II: Simulation and validation of static and dynamic HRV decrease-trigger algorithms to detect stress in firefighters. *Sensors (Basel)*. 2022;22(8). doi:10.3390/s22082925

47. Kirk U, Axelsen JL. Heart rate variability is enhanced during mindfulness practice: A randomized controlled trial involving a 10-day online-based mindfulness intervention. *PLoS One*. 2020;15(12):e0243488. doi:10.1371/journal.pone.0243488

48. Krygier JR, Heathers JAJ, Shahrestani S, Abbott M, Gross JJ, Kemp AH. Mindfulness meditation, well-being, and heart rate variability: a preliminary investigation into the impact of intensive Vipassana meditation. *Int J Psychophysiol*. 2013;89(3):305-313. doi:10.1016/j.ijpsycho.2013.06.017

49. Natarajan A. Heart rate variability during mindful breathing meditation. *Front Physiol*. 2022;13:1017350. doi:10.3389/fphys.2022.1017350

50. Wolkin JR. Cultivating multiple aspects of attention through mindfulness meditation accounts for psychological well-being through decreased rumination. *Psychol Res Behav Manag*. 2015;8:171-180. doi:10.2147/PRBM.S31458

51. Burg JM, Michalak J. The healthy quality of mindful breathing: Associations with rumination and depression. *Cogn Ther Res*. 2011;35(2):179-185. doi:10.1007/s10608-010-9343-x

52. Liao P, Klasnja P, Tewari A, Murphy SA. Sample size calculations for micro-randomized trials in mHealth. *Stat Med*. 2016;35(12):1944-1971. doi:10.1002/sim.6847

53. Seewald NJ, Sun J, Liao P. *MRT-SS Calculator: An R Shiny Application for Sample Size Calculation in Micro-Randomized Trials*; 2016. http://arxiv.org/pdf/1609.00695.

54. Schwerdtfeger AR, Ofner S. Evaluation of a just in time adaptive intervention (JITAI) using additional heart rate variability reductions. Published 2024, February 25. Accessed 2024, December 3. https://osf.io/qkep9

55. Feldman G, Greeson J, Senville J. Differential effects of mindful breathing, progressive muscle relaxation, and loving-kindness meditation on decentering and negative reactions to repetitive thoughts. *Behav Res Ther*. 2010;48(10):1002-1011. doi:10.1016/j.brat.2010.06.006

56. Fincham GW, Strauss C, Cavanagh K. Effect of coherent breathing on mental health and wellbeing: a randomised placebo-controlled trial. *Sci Rep*. 2023;13(1):22141. doi:10.1038/s41598-023-49279-8

57. Adamczyk AK, Wyczesany M, Roelofs K, van Peer JM. Reappraisal is less effective than distraction in downregulation of neural responses to physical threats-An event-related potential investigation. *Psychophysiology*. 2023;60(9):e14316. doi:10.1111/psyp.14316

58. Wolgast M, Lundh L-G. Is distraction an adaptive or maladaptive strategy for emotion regulation? A person-oriented approach. *J Psychopathol Behav Assess*. 2017;39(1):117-127. doi:10.1007/s10862-016-9570-x

59. Kanske P, Heissler J, Schönfelder S, Bongers A, Wessa M. How to regulate emotion? Neural networks for reappraisal and distraction. *Cereb Cortex*. 2011;21(6):1379-1388. doi:10.1093/cercor/bhq216

60. Wadlinger HA, Isaacowitz DM. Fixing our focus: training attention to regulate emotion. *Pers Soc Psychol Rev*. 2011;15(1):75-102. doi:10.1177/1088868310365565

61. Hovsepian K, al'Absi M, Ertin E, Kamarck T, Nakajima M, Kumar S. cStress: Towards a gold standard for continuous stress assessment in the mobile environment. *Proc ACM Int Conf Ubiquitous*

Comput. 2015;2015:493-504. doi:10.1145/2750858.2807526