

Triggered by the Heart: Effectiveness of Two Micro-Randomized Just in Time Adaptive Interventions (JITAIs) for Reducing Stress and Stabilizing Cardiac Autonomic Function

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Triggered by the Heart: Effectiveness of Two Micro-Randomized Just in Time Adaptive Interventions (JITAIs) for Reducing Stress and Stabilizing Cardiac Autonomic Function

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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. Clinical Trial: We confirm to retrospectively register the trial at the German Clinical Trials Register (Germany).

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Original Manuscript

Running Head: JITAIIs triggered by HRV

Triggered by the Heart:

**Effectiveness of Two Micro-Randomized Just in Time Adaptive Interventions (JITAIIs)
for Reducing Stress and Stabilizing Cardiac Autonomic Function**

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Abstract

Background

Heart rate variability (HRV) indicates brain-body interaction and has been associated with a variety of mental and physical health indicators. Transient HRV decreases independent of bodily movement (so-called additional heart rate variability reductions; AddHRVr) potentially reflect moments of psychophysiological vulnerability. This metric is quantified by regressing bodily movement on the root mean square of successive differences (RMSSD) and identifying reductions below 0.5 *SD* of the predicted value in real-time in everyday life.

Objective

We applied this measure by means of wearables in everyday life to trigger low-threshold 1-min just in time adaptive interventions (JITAIs) with the aim to stabilize autonomic function and relieve perceived stress and ruminative thoughts. Thus, moments of AddHRVr were compared with random points in time with respect to the effects of brief JITAIs.

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 slow-paced breathing) following each prompt and in Study 2, $N = 50$ participants were micro-randomized to both an external attention (i.e., focusing attention to a non-living object) and mindful breathing intervention. HRV was assessed prior, during and following each intervention by means of the root mean squares of successive differences (RMSSD), standard deviation of normal-to-normal beats (SDNN) as well as high and low frequency HRV. Participants also reported on perceived stress and ruminative thoughts pre and post intervention.

Results

Following interventions in both studies, perceived stress and ruminative thoughts significantly declined irrespective of the kind of prompt and intervention (Study 1: perceived stress: $b = -0.12$, $p < .001$; ruminative thoughts: $b = -0.11$, $p < .001$; Study 2: perceived stress: $b = -0.07$, $p = .011$; ruminative thoughts: $b = -0.10$, $p = .002$). AddHRVr-triggered prompts resulted in a stronger increase in HRV during the slow-paced breathing ($b = 0.08$, $p = .015$) and mindful breathing interventions ($b = 0.10$, $p = .026$), and elevated HRV metrics in a time frame of 10 minutes following the interventions in contrast to random prompts (Study 1: $b = 0.12$, $p < .001$; Study 2: $b = 0.10$, $p = .027$).

Conclusions

Both studies show for the very first time that transient, non-metabolic reductions in HRV (AddHRVr) can be used to trigger brief JITAI real-time by wearables to stabilize autonomic function, thus potentially promoting cardiac health. Findings suggest that although psychological benefits emerged independent of the cardiac autonomic state, slow-paced breathing or directing attention for 1 minute to either the own body or non-living objects seemed to boost autonomic flexibility when HRV was compromised.

Trial Registrations: German Clinical Trial Register: DRKS00035684 (<https://drks.de/register/de/trial/DRKS00035684/preview>),
DRKS00035685 (<https://drks.de/register/de/trial/DRKS00035685/preview>)

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

Introduction

Life is not always sunny and we regularly 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, JITAs [3–5]) could prove a highly effective treatment and prevention strategy for an increasingly stressed population. 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 [6]. Thus, the aim of this research was to validate JITAs designed to reduce stress and perseverative cognition (ruminative thoughts) as well as autonomic dysregulation by leveraging transient non-metabolic decreases in cardiac vagal regulation (so-called additional heart rate variability reductions; AddHRVr [7,8]).

HRV and particularly the root mean square of successive differences (RMSSD) metric of HRV is considered to reflect vagally-mediated HRV (vmHRV) and could thus 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 [9–11]. 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 [10,12,13]. 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 JITAIs, addressing both physiological and psychological indices of well-being.

Recently, we proposed a simulation-based approach to determine individualized trigger settings for AddHRVr and assess their sensitivity for psychosocial states [14]. This approach is based on RMSSD as a measure of vagally sensitive HRV and involves two steps (for an overview, please refer to Fig. A1 in the Supplements): First, a calibration period aims to derive personalized regression parameters for the algorithm. Specifically, using 1-minute segments of data across a day (12h), RMSSD is regressed on bodily movement for each individual. The algorithm then uses individualized RMSSD thresholds ($> 0.5 SD$) to identify segments with significant RMSSD reduction compared to predicted values derived from the calibration. Such additional (i.e., non-metabolic) HRV reductions (AddHRVr [7,8]) are tracked in the following days and a trigger is emitted when a predefined number of AddHRVr occur within a specific time interval [15]). Since AddHRVr is a metric provided every minute and short-term reductions in RMSSD independent of bodily movement could signal diverse psychosocial states including positive affect [16], the exact number of segments in a pre-defined time window is crucial for the validity of an AddHRVr-trigger. Notably, in our previous simulation study varying the analysis 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 a good performance of this trigger setting [14]. Precisely, when 13 1-min segments of RMSSD in a time window of roughly half an hour (28 minutes) were at least $0.5 SD$ lower than predicted given a certain amount of bodily movement (signaling AddHRVr), adverse psychosocial feeling states could be predicted with good power. Hence, we used this algorithm setting (“13 out of 28”) to trigger JITAIs in two independent studies. We decided for two independent studies in order to reduce complexity of the design and

allow replication in two independent samples.

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; approximately 6 breaths/minute) has been suggested as a powerful and easy to learn technique to improve both mental and physical functions [17–21]. In particular, 0.1 Hz breathing has a direct effect on autonomic regulation via strengthening vagal afference and stimulating the baroreceptor reflex, which also positively affects higher central nervous system functioning [10,20]. 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 [10,22–24]. Other research reported a reduction in anxiety and perceived stress following 0.1 Hz breathing [20,25], although experimental research could not confirm significant effects for acute stress reactivity [26]. Beneficial effects of slow-paced breathing have also been reported for individuals with hypertension and cardiovascular disorders, thus confirming its clinical usefulness [27,28]. Taken together, slow-paced breathing at 0.1 Hz could benefit both autonomic regulation and psychological health. It is easy to learn and can be applied unobtrusively in various daily life contexts (e.g., during work, leisure time or while being on the way) via smartphones [29,30].

Study 2: Mindful breathing

Of note, previous research could show that brief mindfulness (breathing) exercises might be effective in increasing HRV [31–34] and improving well-being via reducing distress and rumination [35,36]. Mindful breathing refers to a technique that aims to facilitate staying in contact with (i.e., directing attention to) the own breath in a non-judgmental way. 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. 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.

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 [37] performed breathing exercises of 1 minute contingent to a prompt on their smartphone. We hypothesized that perceived stress and ruminative thoughts would diminish more strongly following 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.

Likewise, 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. We hypothesized that mindful breathing exercises would decrease perceived stress and rumination and increase HRV relative to an external attention exercise.

Methods

Participants

Study 1

Overall, 69 individuals participated in the ecological momentary assessment (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 ($n = 2$), resulted in a final sample of 60 participants (45 women; 15 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. Inclusion criteria were age between 18 and 45 years, no self-reported cardiovascular or mental disorders and no self-reported psychotropic or cardiovascular medication. A power analysis was conducted a priori based on simulation studies [38], 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 2

A power analysis for micro-randomized trials was conducted using the tool MRT-SS [39,40]. 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 to detect also smaller-sized effects. The final sample comprised of $N = 51$ participants, of whom 39 (76%) were women and 12 were men. The same inclusion/exclusion criteria were applied as in Study 1. 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% 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 $N = 50$.

Ethical considerations

Both studies were approved by the local ethics committee (Study 1: GZ. 39/93/63 ex 2022/23; Study 2: GZ. 39/54/63/ ex 2023/24) and pre-registered via OSF (Study 1 [37], Study 2 [41]). Written informed consent was obtained for both studies and trials were registered at the German Clinical Trials Register (Study 1: DRKS-ID: DRKS00035684; Study 2: DRKS-ID: DRKS00035685). Participants were explicitly informed about the psychological concepts of the studies, study duration, the concepts of JITAIs as well as the interventions applied. They agreed that data would be analyzed in summary form and used for scientific purposes only (including publication). They were informed that they could withdraw participation any time without giving reasons and could request deletion of their data upon request. They were also informed to get information in case ectopic beats or arrhythmias would be detected to allow clarification by a cardiologist. Data were pseudo-anonymized via a personal code not attached to names or other identifying information. Participants received no financial compensation for participation, but could receive course credit if applicable.

Study Design

Study 1

The study followed a micro-randomized design [42,43] triggering a brief intervention either by episodes of psychophysiological vulnerability (AddHRVr-trigger) or at random times. The design is outlined in Figure 1.

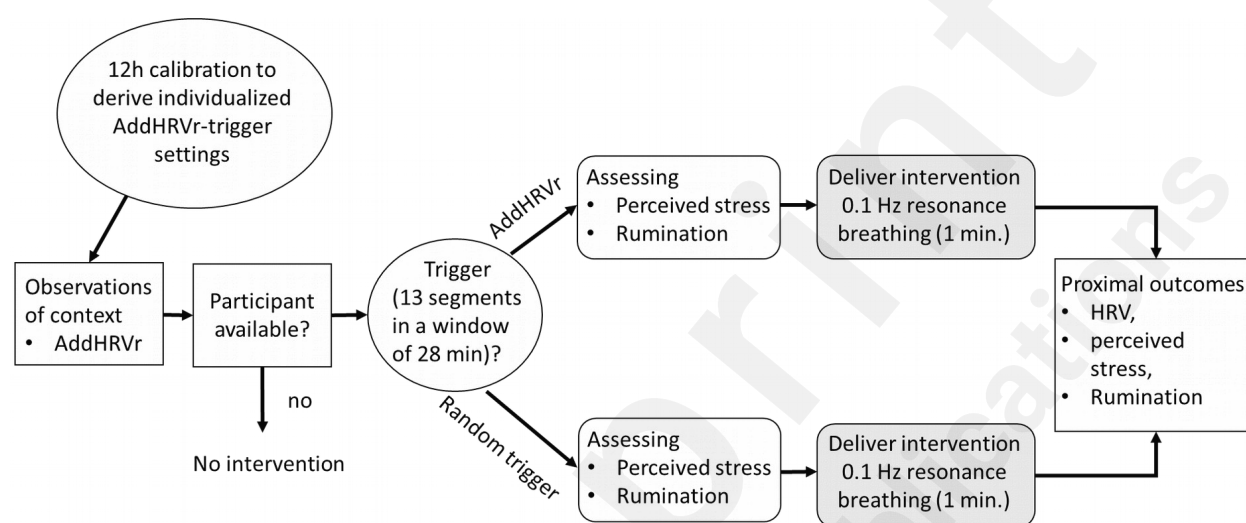


Fig. 1. Schematic illustration of the procedure of Study 1. A slow-paced breathing intervention (0.1 Hz) was either triggered at random points in time or contingent to additional (i.e., non-metabolic) heart rate variability reductions (AddHRVr).

Using a calibration period of 12h, we derived the regression parameters slope and intercept for each individual (descriptive statistics, see Multimedia Appendix 2: Table A1) and fed these parameters into the real-time working algorithm for the subsequent days. Based on these personalized regression parameters, the intervention was triggered either when RMSSD was 0.5 *SD* below the predicted value in 13 minutes during a time frame of 28 minutes (AddHRVr-trigger), or at random times (Multimedia Appendix 1: Fig. A1). Prior to each intervention and immediately thereafter, participants provided ratings of perceived stress and ruminative thoughts, and HRV (i.e., RMSSD) was recorded 10 minutes before the intervention, during the intervention and 10 minutes thereafter. 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).

Study 2

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. 2).

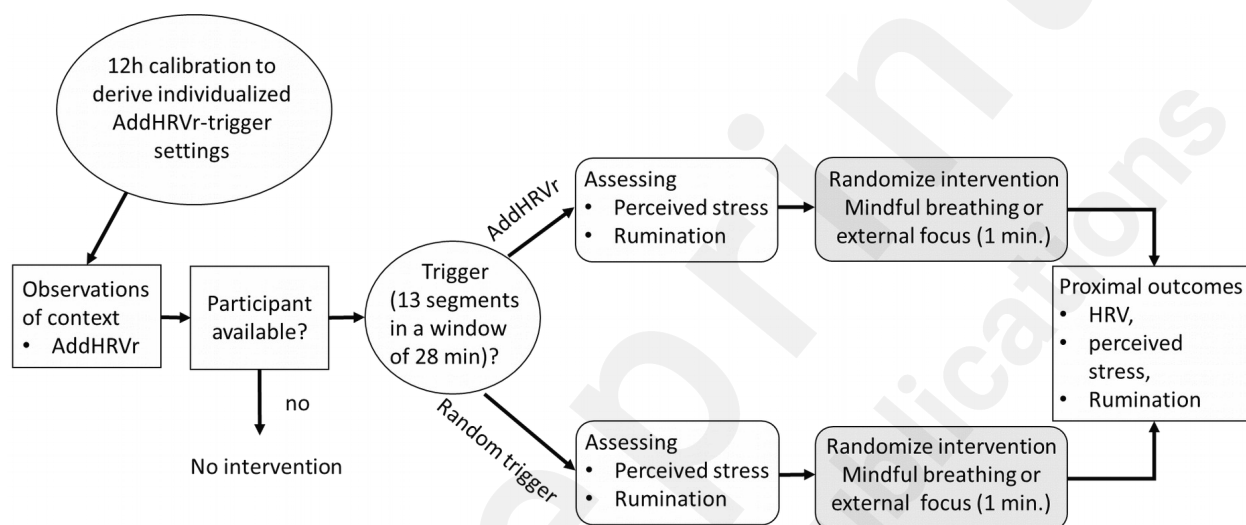


Fig. 2. Schematic illustration of the procedure of Study 2. Two interventions requiring attention either to internal or external cues (see, Fig. 4) were either triggered at random points in time or contingent to additional (i.e., non-metabolic) heart rate variability reductions (AddHRVr).

Variables and Instruments

Perceived stress

Perceived stress was assessed via four items adapted from the Perceived Stress Scale [44,45]. 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 to yield a mean score of perceived stress. In order to evaluate reliability of this measure, generalizability theory analysis [46] was applied via the package psych (v2.4.3 [47]) in R (v4.4.0 [48]). Generalizability theory analysis allows to distinguish reliability of the measure in reliability between persons (comparable to traditional measures of internal consistency) and within persons. For Study 1, between-person reliability was excellent (pre intervention: $R_{KRn} = .98$, post intervention: $R_{KRn} = .99$) documenting, that differences in stress ratings between individuals could be assessed highly reliable. Moreover, within-person reliability (pre intervention: $R_{Cn} = .68$, post intervention: $R_{Cn} = .69$) seemed satisfactory, thus indicating that the assessment of change within each person was reliable. 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.

Likewise, for Study 2, 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: $R_{Cn} = .65$). 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

In Study 1, ruminative thoughts were assessed via a single item measure. In particular, following previous research [49], 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." Upon every prompt, this introduction was presented followed by the question: "Does this apply to you at the moment?" 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.

In Study 2, ruminative thoughts were assessed with a slightly adjusted item from Study 1 as published by Du et al. [50]: “I’m recalling all my shortcomings, failures and the things that I did wrong”. We decided for this alternative assessment instead of the rather long introductory text applied in Study 1 for time economic reasons. Answers were given on a 5-point Likert scale between the poles 1 (“does not apply”) and 5 (“does fully apply”). 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.

HRV

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; see Multimedia Appendix 2: Table A1). 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 and emit a trigger in the subsequent 3 days (from Wednesday to Friday [15]) to initiate smartphone prompts. As previously outlined, the trigger was emitted when 13 1-min segments of RMSSD in a time window of roughly half an hour (28 minutes) were at least $0.5 SD$ lower than predicted given a certain amount of bodily movement (Multimedia Appendix 1: Fig. A1). AddHRVr-triggers were complemented by random triggers. For AddHRVr-triggers we applied a silent setting of 60 minutes, meaning that one AddHRVr trigger was emitted per hour at maximum.

Metabolic equivalents (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.

Just in time adaptive interventions

Study 1: 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. 3). 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) [10,20,24]. 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. Exact instructions can be found in the Multimedia Appendix 3: Instructions.

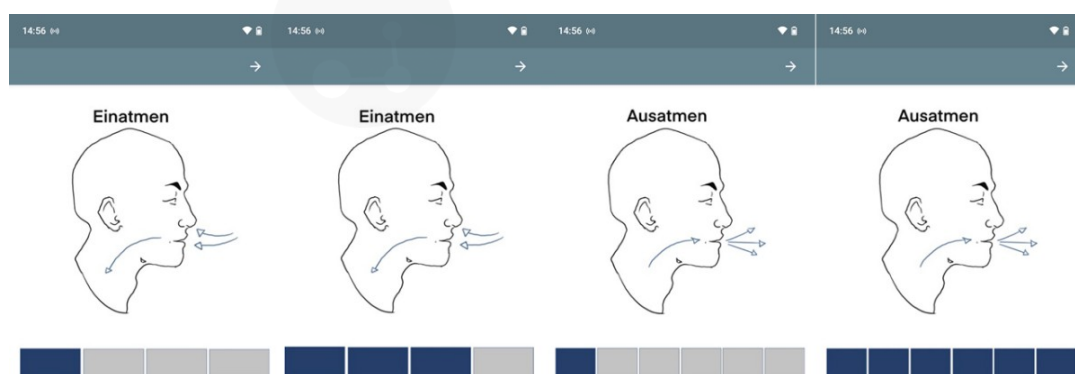


Fig. 3. App-based 0.1 Hz breathing intervention. Inhalation (“Einatmen”) was paced for 4 seconds

and exhalation (“Ausatmen”) for 6 seconds as guided by a progress bar.

Study 2: Mindful breathing and external cues intervention

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 [51] and calming effects on cardiac activity [31–33] resulting from mindful breathing. Regarding the external focus exercises, participants were instructed to focus on a neutral, non-living object in their surroundings. Interventions are visualized in Figure 4. Detailed instructions can be found in the Multimedia Appendix 3: Instructions.



Fig. 4. 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.

Pre-registration and deviation thereof

Study 1

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. Second, we specified to control for smoking, age, gender, and 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. Third, we did not specify the HRV measure as the outcome variable in the pre-registration. However, as outlined in previous research, RMSSD is considered a core measure of this approach [7,8,14]. Nevertheless, in order to evaluate a broader spectrum of HRV trajectories prior to and following the intervention as recommended by some authors [52], we additionally analyzed the standard deviation of normal inter-beat intervals (SDNN), which is considered an indicator of autonomic regulation of HRV [52] and the vagally-sensitive high frequency range of HRV (HF-HRV; 0.15 - 0.40 Hz) to avoid selective reporting of HRV measures.

Study 2

We pre-registered five hypotheses in this pre-registration [41]. In order to align this research with Study 1, 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).

Data parametrization and statistical analysis

In Study 1, participants received on average 45 prompts ($SD = 8.38$; range: 31 – 65), of which 69% were answered, 4% were dismissed, 19% were ignored and 8% incomplete. Noteworthy, $n = 20$ (32%) of the sample received AddHRVr-triggers, while $n = 40$ (68%) did not. On average, $M = 4.14$ ($SD = 7.10$) AddHRVr-triggers were emitted with an interindividual range between 0 and 26. In Study 2, participants received on average 43 prompts ($SD = 11.97$; range: 24 – 71), of which 60% were answered, 7.5% were dismissed, 29% were ignored and 1% incomplete. Of note, $n = 6$ (12%) of the sample received no AddHRVr-triggers, while the remaining participants ($n = 44$; 88%) received between 1 and 39 AddHRVr-triggers. On average, $M = 14.41$ ($SD = 10.72$) AddHRVr-triggers were emitted per individual, which was considerably more than in Study 1.

To evaluate the effectiveness of the JITAI, we applied multilevel (mixed effects) models predicting perceived stress, rumination and RMSSD, respectively, by AddHRVr trigger (vs. random trigger) and time (pre vs. intervention and pre vs. post intervention) and the interaction of these variables. For Study 2, intervention type (mindful breathing vs. external focus) was additionally added to the models. We used RMSSD as the core outcome variable of HRV, because it has been particularly recommended in previous ambulatory research [53] and represents the most often studied ambulatory marker of vagally-mediated HRV [54–56]. RMSSD was quantified as the mean of the 10 minutes prior to each prompt. Importantly, we controlled 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). RMSSD was analyzed in a time frame of 10 minutes prior to the intervention (coded as -1), during the interventions (coded as 0) and the following 10 minutes (coded as 1). Of note, in order to evaluate effects during the interventions, we applied a time frame of ± 2 minutes to account for potential inaccuracy of timing between smartphones and EcgMove4-devices.

In order to evaluate the robustness of intervention effects on HRV, we also analyzed HF-HRV

and SDNN [52]. Specifically, HF-HRV is considered a frequency-domain indicator of vagally-sensitive HRV and SDNN indicates overall autonomic regulation of cardiac activity. In order to compare adherence with the 0.1 Hz breathing interventions during both types of triggers (AddHRVr vs. random) in Study 1, we also analyzed low-frequency HRV (LF-HRV; 0.04 – 0.15 Hz) during the interventions. 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) [20]. HRV measures were logarithmized prior to analysis to account for skewness.

The interaction between prompt (random vs. AddHRVr) and time (pre vs. intervention and pre vs. post intervention) would indicate the effectiveness of the AddHRVr-triggered intervention on the above-mentioned outcome variables. For analyzing Study 2, we also centered intervention type within persons. Throughout analyses, we additionally controlled for age, gender, BMI, METs, and momentary smoking. Since age, gender and BMI did not change any of the associations of interest, they were removed from the final models. Continuous predictor variables were centered. Moreover, we centered trigger and intervention (Study 2) on the within-person level to allow interpretation of within-person effects [57].

Analyses were conducted using R (v4.4.0 [48]) with the package lme4 (v1.1-35.3 [58]). Note that *b* refers to the unstandardized estimate of the relationships. We fixed the level of significance at $p < .05$ (two-tailed).

Results

Study 1

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. Precisely, we predicted logarithmized LF-HRV 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, $\ln$ RMSSD 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 1.

Table 1. Multilevel regression predicting logarithmized RMSSD before (pre), during (intervention) and after the slow-paced breathing intervention (post intervention). Note that Estimates refer to raw b-values (slopes) and CI to confidence intervals.

Predictors	lnRMSSD		
	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
Time (pre vs. intervention [breathing])	0.17	0.16 – 0.19	<.001
Time (pre vs. post intervention)	0.03	0.02 – 0.04	<.001
Trigger × time (pre vs. intervention [breathing])	0.08	0.02 – 0.14	.015
Trigger × time (pre vs. post intervention)	0.12	0.07 – 0.16	<.001

Random Effects

σ^2	0.23
τ_{00} 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 AddHRVr-triggers as compared to random triggers (trigger by time (pre. vs. intervention): $b = 0.08$; $p = .015$). Most importantly, lnRMSSD remained significantly higher 10 minutes after the intervention in the AddHRVr-trigger condition as compared to the random trigger condition (trigger by time (pre vs. post intervention): $b = 0.12$; $p < .001$). Furthermore, increasing METs and concurrent smoking were accompanied by significantly lower lnRMSSD (main effect MET: $b = -0.35$, $p < .001$; main effect smoking: $b = -0.03$, $p = .028$). The RMSSD-trajectories for both trigger conditions are visualized in Figure 5 (note that we use unadjusted raw scores here to allow for evaluating the plausibility of the data).

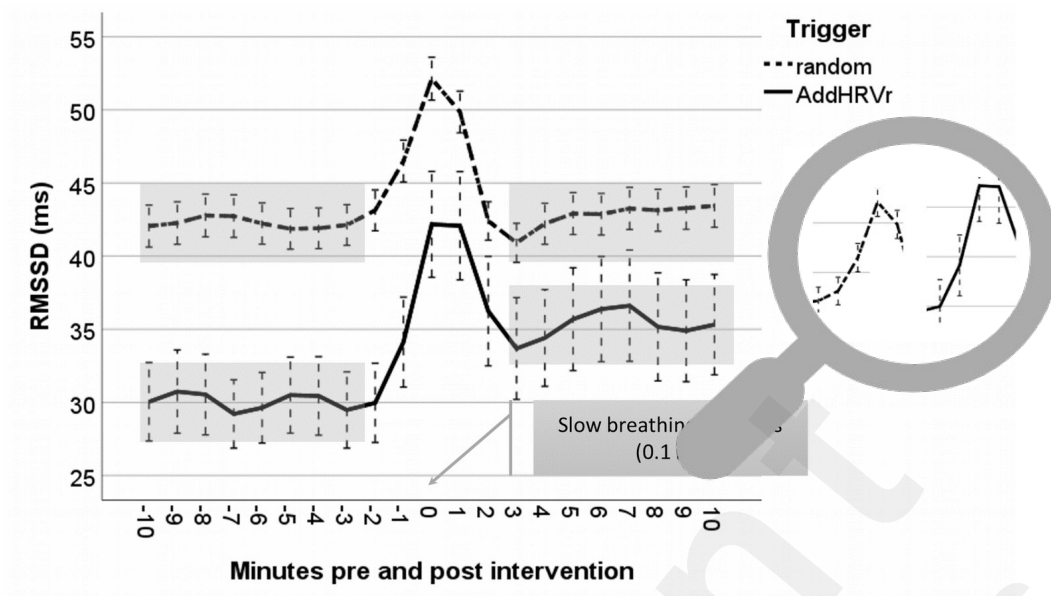


Fig. 5. Trajectories of vagally-mediated HRV (root mean squares of successive differences; RMSSD) 10 minutes before and after the prompt, respectively. The upper stippled line represents RMSSD following random prompts and the lower solid line indicates RMSSD following an AddHRVr-trigger. Stippled whiskers indicate 95% confidence intervals. Note, the shadowed areas visualize the significant interaction between trigger and pre-post assessment and the stronger increase in RMSSD to the AddHRVr-triggered intervention is magnified on the right side.

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 (trigger by time (pre vs. intervention): $b = 0.16$, $p = .014$; trigger by time (pre. vs. post intervention): $b = 0.21$, $p < .001$) and partially significant for lnSDNN (trigger by time (pre vs. intervention): $b = 0.05$, $p = .067$; trigger by time (pre vs. post intervention): $b = 0.06$, $p < .001$), thus suggesting general effectiveness of the JITAI on HRV.

Evaluating spontaneous recovery of HRV

In a final step, we aimed to evaluate whether the increase of HRV (in particular, RMSSD) following the intervention is specific to the intervention or merely 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 offline for potential AddHRVr-triggers that were not evoked (e.g., because the silence period prevented an additional prompt). In the following, we refer to these triggers as virtual AddHRVr-triggers, because they show the same characteristics as the AddHRVr-trigger (13 segments in a time window of 28 minutes), but had never been evoked real-time. We then calculated the interaction between trigger type (virtual AddHRVr-triggers vs. random triggers vs. regular AddHRVr-triggers) and time (10 minutes pre vs. 10 minutes post intervention). The interaction effect trigger (virtual vs. regular AddHRVr) by time (pre vs. post intervention) was highly significant ($b = 0.08$, $p < .001$; see Multimedia Appendix 4: Table A3), indicating that RMSSD increased more strongly following AddHRVr-triggers with intervention (relative to pre-intervention) than following virtual AddHRVr-triggers.

Study 2

Perceived stress and rumination

Like in Study 1, we found significant effects of time (pre vs. post) 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 time (pre-vs. intervention phase; $b = 0.10$, $p = .026$), thus suggesting that the change from pre to intervention phase differed as a function of trigger and intervention type (Table 2). 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 time (pre vs. intervention) 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 time (pre vs. intervention) was not significant ($b = -.01$, $p = .627$; Fig. 6, top lines left and right), thus indicating that following random triggers, both types of interventions resulted in roughly the same increase in RMSSD. Of note, when the AddHRVr-trigger was set to reference, the interaction was significant ($b = 0.07$, $p = .013$), thus documenting that when triggered by 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 time (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 an AddHRVr-trigger, RMSSD significantly increased from pre to post intervention period as compared to when triggered randomly. Hence, any of the interventions performed following an AddHRVr-trigger resulted in an increase of 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 ($b = -0.22$, $p < .001$) and when participants smoked ($b = -0.28$, $p < .001$).

Table 2. Multilevel regression predicting logarithmized RMSSD before (pre), during (intervention) and after intervention (post intervention) to both types of triggers. Note that Estimates refer to raw b-values (slopes) and CI to confidence intervals.

<i>Predictors</i>	lnRMSSD		
	<i>Estimates</i>	<i>CI</i>	<i>p</i>
(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 (mindful breathing vs. external focus)	-0.02	-0.04 – 0.00	.047
Time (pre vs. intervention)	0.08	0.07 – 0.10	<.001
Time (pre vs. post intervention)	0.04	0.03 – 0.06	<.001
Trigger × intervention	-0.07	-0.11 – -0.02	.003
Trigger × time (pre vs. intervention)	0.04	-0.00 – 0.08	.054
Trigger × time (pre vs. post intervention)	0.09	0.06 – 0.12	<.001
Intervention × time (pre vs. intervention)	0.03	-0.01 – 0.07	.104
Intervention × time (pre vs. post intervention)	-0.00	-0.03 – 0.03	.931
Trigger × intervention × time (pre vs. intervention)	0.10	0.01 – 0.18	.027
Trigger × intervention × time (pre vs. post intervention)	0.04	-0.02 – 0.10	.230
Random Effects			
σ^2	0.21		
τ_{00} 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.

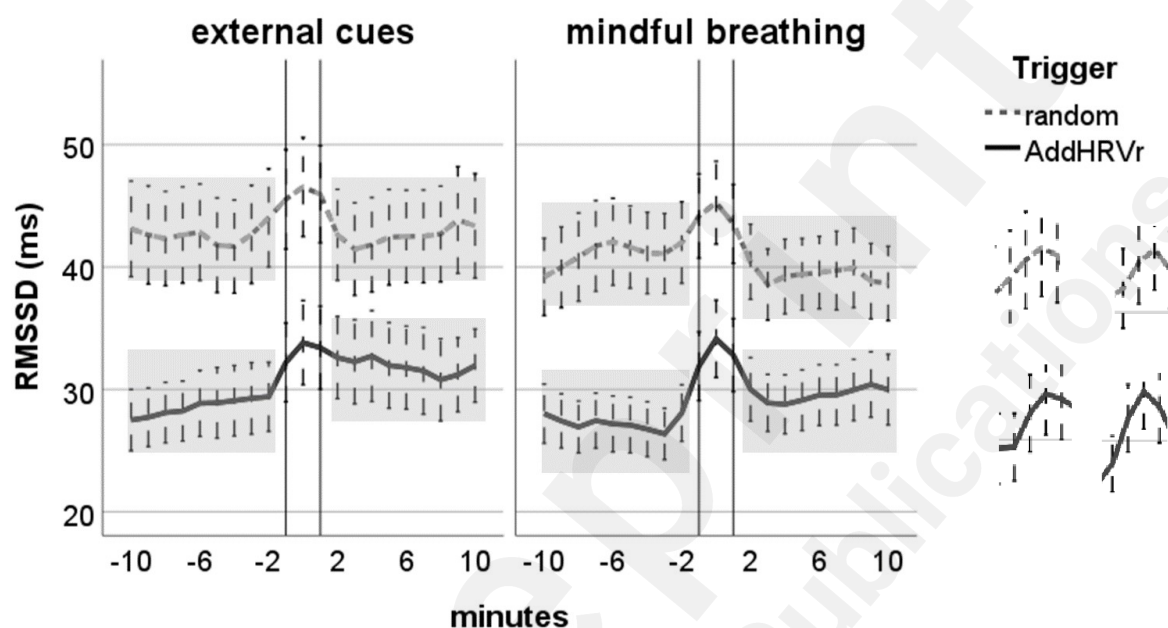


Fig. 6. Trajectories of vagally-mediated HRV (root mean squares of successive differences; RMSSD) 10 minutes before and after the prompt, respectively. The upper stippled line represents RMSSD following random prompts and the lower solid line indicates RMSSD following an AddHRVr-trigger. The external attention intervention (external cues) is depicted on the left side and the mindful breathing intervention on the right side. Stippled whiskers indicate 95% confidence intervals. Note, the shadowed areas visualize the significant interaction between trigger and pre-post assessment and the stronger increases in RMSSD to the AddHRVr-triggered interventions are magnified on the right side.

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 time (pre- vs. 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 and confirming the stronger HRV increase to the AddHRVr-triggered mindful breathing interventions. Furthermore, the two-way interaction between trigger and time (pre vs. post intervention phase) could be confirmed for both lnHF-HRV ($b = 0.17$, $p < .001$) and lnSDNN ($b = 0.05$, $p < .001$), respectively. Hence, the generally facilitating recovery effects of both types of interventions appeared robust for different HRV metrics.

Evaluating spontaneous recovery of HRV

Mirroring the approach of Study 1, we finally evaluated whether the increase in HRV after both interventions contingent to AddHRVr-triggers was higher as compared to a spontaneous rebound effect of HRV following offline determined virtual AddHRVr-triggers (without interventions). The interaction between trigger (virtual AddHRVr-trigger vs. AddHRVr-trigger with intervention) and time (pre vs. post intervention) was significant ($b = 0.07$, $p < .001$; see Multimedia Appendix 5: Table A3), thus documenting that AddHRVr-triggered interventions resulted in a significantly stronger increase in RMSSD as compared to virtual AddHRVr-triggers without interventions. Hence, the applied interventions seemed to drive the boosting effect on HRV and not a spontaneous rebound following low HRV. Interestingly, the effect size was similar to that of Study 1.

Discussion

The aim of both studies was to evaluate the effectiveness of physiologically triggered (i.e., AddHRVr) JITAIs to restore psychological well-being and autonomic flexibility. In Study 1 we used a brief (1-minute) slow-paced breathing intervention and in Study 2 we applied brief mindful breathing and external focus exercises. Findings document that such 1-minute interventions resulted in a general decline of stress and rumination, independent of the right moment. Second and foremost,

both slow-paced breathing and mindful breathing interventions applied at the moments of compromised cardiac vagal function (i.e., following AddHRVr-triggers) resulted in a stronger (re-) increase of HRV. Precisely, we observed higher HRV during the breathing interventions and up to 10 minutes thereafter, if the intervention was triggered by AddHRVr as compared to randomly triggered prompts. It should be mentioned in this respect that in Study 2 the re-increase in HRV following the interventions could also be observed for the external focus exercises, thus suggesting a rather non-specific intervention effect in re-establishing autonomic flexibility.

Importantly, AddHRVr contingent increases in HRV during and after the interventions could be verified for different indices of HRV (namely RMSSD, HF-HRV and SDNN), thus suggesting rather broad-banded beneficial effects on cardiac autonomic regulation. Hence, triggering brief interventions in moments of low HRV could prove particularly beneficial for stabilizing cardiac autonomic regulation, thus arguing for the just in time intervention concept. Importantly, the cardiac vagal rebound relative to pre-intervention levels observed in both studies was more pronounced than could normally be expected without interventions. Specifically, analyzing responses to so-called virtual AddHRVr-triggers (non-metabolic HRV decreases that did not evoke triggers, but showed the same characteristics like the AddHRVr-triggers) suggested that the increase in HRV following the AddHRVr-triggered interventions was significantly more pronounced than the natural increase of HRV following virtual AddHRVr-triggers, thus excluding the interpretation of spontaneous rebound effects. Thus, it seems that shifting attention to either internal or external cues or engaging in slow breathing exercises was a main driver for the increase in cardiac autonomic flexibility.

Findings of Study 1 generally align with research suggesting beneficial effects of slow breathing on emotional valence, perceived stress and anxiety in controlled settings [18,59,60]. Moreover, the finding confirms research showing that a slow breathing biofeedback increased attentional control in individuals reporting higher levels of stress [61], suggesting that slow breathing exercises are particularly useful when applied during elevated (physiological) stress. Moreover, the

conceptual replication in Study 2 confirms research on the beneficial effects of mindful breathing for mental health [35,36,63]. However, we need to emphasize that, like in Study 1, in contrast to the 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 [62].

Since any of the interventions applied seemed to benefit both rumination and perceived stress independent of the cardiac autonomic state, 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 [63], especially when combined with acceptance [64]. 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 [65]. 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 [66]. Taken together, we would assume that the psychological effectiveness of the JITAs applied in this research was mainly driven by deployment of attention.

Limitations and recommendations

The studies had some limitations that need to be acknowledged. First and foremost, they 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 interventions. Consequently, unlike HRV, the psychological variables do not strongly argue for a just in time approach. Certainly, more research is warranted examining the exact circumstances under which participants will benefit more strongly with respect to their psychological

well-being. Alternatively, refining the trigger settings to detect psychologically vulnerable periods in time with higher accuracy and adapt the interventions to the specific needs constitutes an important task for future research [67].

Second, sample sizes for both studies were rather moderate and the general levels of perceived stress and rumination were rather low. Future research should increase both sample sizes and days of assessment and assess more heterogeneous samples with compromised well-being to uncover effects with higher sensitivity, especially also the superiority of AddHRVr-triggered interventions for perceived stress and rumination.

Third, there was no passive 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 for 1 minute may benefit well-being and cardiac autonomic regulation. Accordingly, Study 2 suggests that effects on psychological variables might indeed be unspecific to the intervention applied. Relatedly, we cannot rule out that the reduction of perceived stress and rumination indicated mere order effects or psychological adaptation to the repeated assessment, or even socially desirable responding. Taken together, a control group without interventions or a within-person condition without intervention is needed in future research to ascribe effects solely to the interventions.

Fourth, while we analyzed immediate and delayed cardiac autonomic effects of the interventions, 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. Fifth, 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. Notably, the same trigger settings deemed more suitable in Study 2 with 88% of the sample receiving

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 beyond the levels performed during the calibration period, algorithm settings could prove faulty, thus leading to 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 [67] adjusting the intercept, which could account for shifts in autonomic regulation towards higher or lower levels of RMSSD. Furthermore, easier to handle algorithms might allow to scale up the application of JITAs by means of commercially available wearables.

Finally, although this research indicated that JITAs triggered by non-metabolic decreases of 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 regimens. For example, it would be important to know if such brief interventions when conducted regularly over a longer period of time would have the potential to decrease risk for cardiovascular or mental diseases beyond the effects achieved by traditional intervention regimens.

Conclusions

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 autonomic 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 [10,19,20,23,36,59]. To our knowledge, these are the very first micro-randomized trials using an AddHRVr algorithm to automatically identify moments of psychophysiological vulnerability and trigger brief interventions (for a similar approach using physiological data, see [69]). The findings

are particularly important as they suggest that intervening at moments of compromised HRV could immediately boost cardiac autonomic function and any kind of intervention could prove successful in restoring HRV up to 10 minutes to a certain degree. Findings were not restricted to a specific HRV metric, but showed evidence towards a generalized increase in cardiac autonomic flexibility, thus supposing clinical relevance. As speculated earlier, distraction or attentional deployment might be the core driver of these effects. In a similar vein, the general relieving effect on perceived stress and rumination independent of the trigger and type of intervention may signal a time out effect potentially restoring well-being.

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 [70]. However, research is yet in its infancy and future studies need to convincingly demonstrate that JITAIs are superior to traditional intervention regimens and worth the tremendous effort in setting up algorithms sensitive and specific to certain psychophysiological states (e.g., stress). In this respect, the adaptive part of JITAIs needs yet to be established. The proposed approach in this research did not adapt interventions to the specific needs, but mainly followed the just in time concept.

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 brief psychological exercises of 1-minute length applied in moments of compromised autonomic flexibility (low non-metabolic heart rate variability) restored autonomic function and benefitted psychological well-being. Findings suggest that brief psychological interventions can be

implemented in daily life via wearables, possibly promoting mental and physical health longitudinally.



Multimedia Appendix 1: Schematic representation of the individually adjusted AddHRVr algorithm based on RMSSD and bodily movement. Adapted with permission from Zeitschrift für Psychologie (2023), 231(4), 291–301. © 2023 Hogrefe Publishing www.hogrefe.com <https://doi.org/10.1027/2151-2604/a000537>

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

Multimedia Appendix 3: Multilevel regression predicting logarithmized RMSSD before (pre), during (intervention) and after the slow-paced breathing intervention (post intervention) to three kind of triggers (virtual AddHRVr, random, AddHRVr). Note that Estimates refer to raw b-values (slopes) and CI to confidence intervals.

Multimedia Appendix 4: Multilevel regression predicting logarithmized RMSSD before (pre), during (intervention) and after intervention (post intervention) to three types of triggers (virtual AddHRVr, random, AddHRVr). Note that Estimates refer to raw b-values (slopes) and CI to confidence intervals.

Multimedia Appendix 5: Intervention Instructions Study 1 and Study 2.

Abbreviations

AddHRVr: Additional (i.e., non-metabolic) heart rate variability reductions

BMI: Body mass index

EMA: Ecological momentary assessment

HRV: Heart rate variability

JITAI: Just in time adaptive intervention

METs: Metabolic equivalents

RMSSD: Root mean square of successive differences

SDNN: Standard deviation of normal-to-normal heart beats

LF-HRV: Low-frequency heart rate variability

HF-HRV: High-frequency heart rate variability

vmHRV: vagally-mediated heart rate variability

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Data Availability

The datasets generated or analyzed during this study are available from the corresponding author on reasonable request

Conflict of Interest

The authors declare no conflicts of interest.

Author Contributions

ARS: Conceptualization, Formal analysis, Methodology, Project administration, Resources, Supervision, Visualization, Writing – original draft, Writing – review & editing

CR: Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing

JMT: Conceptualization, Methodology, Investigation, Visualization, Writing – review & editing

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Supplementary Files

Figures

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).

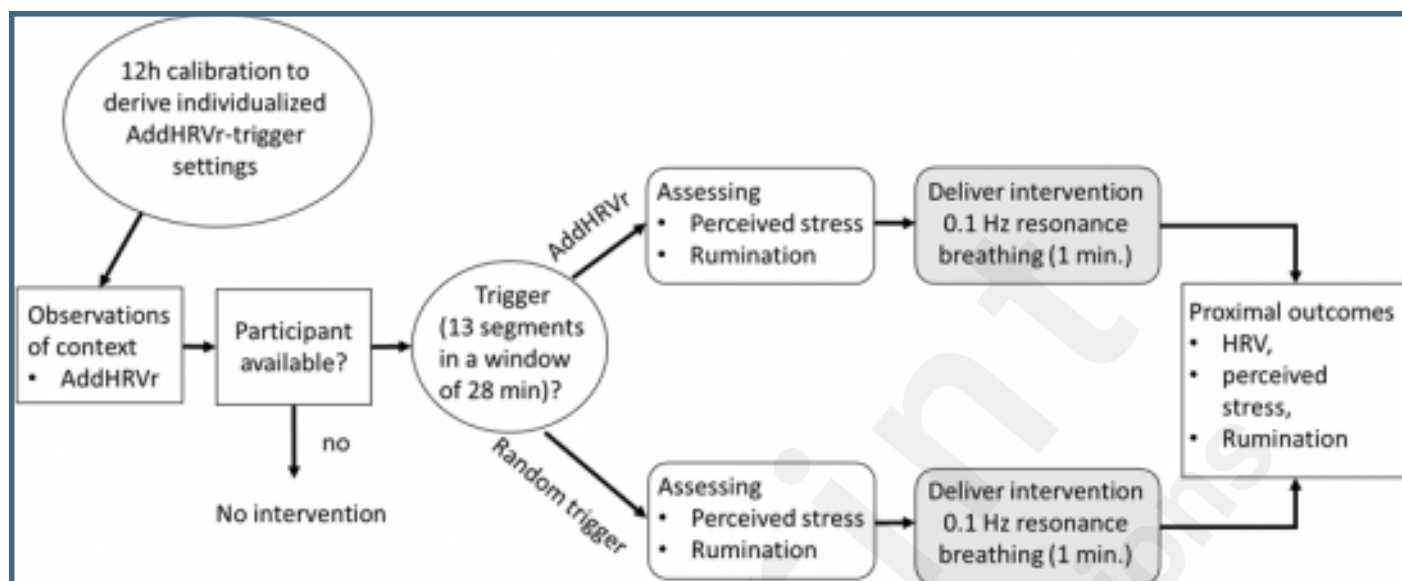


Fig. 2. Schematic illustration of the procedure of Study 2. Two interventions requiring attention either to internal or external cues (see, Fig. 5) were either triggered at random points in time or contingent to additional (i.e., non-metabolic) heart rate variability reductions (AddHRVr).

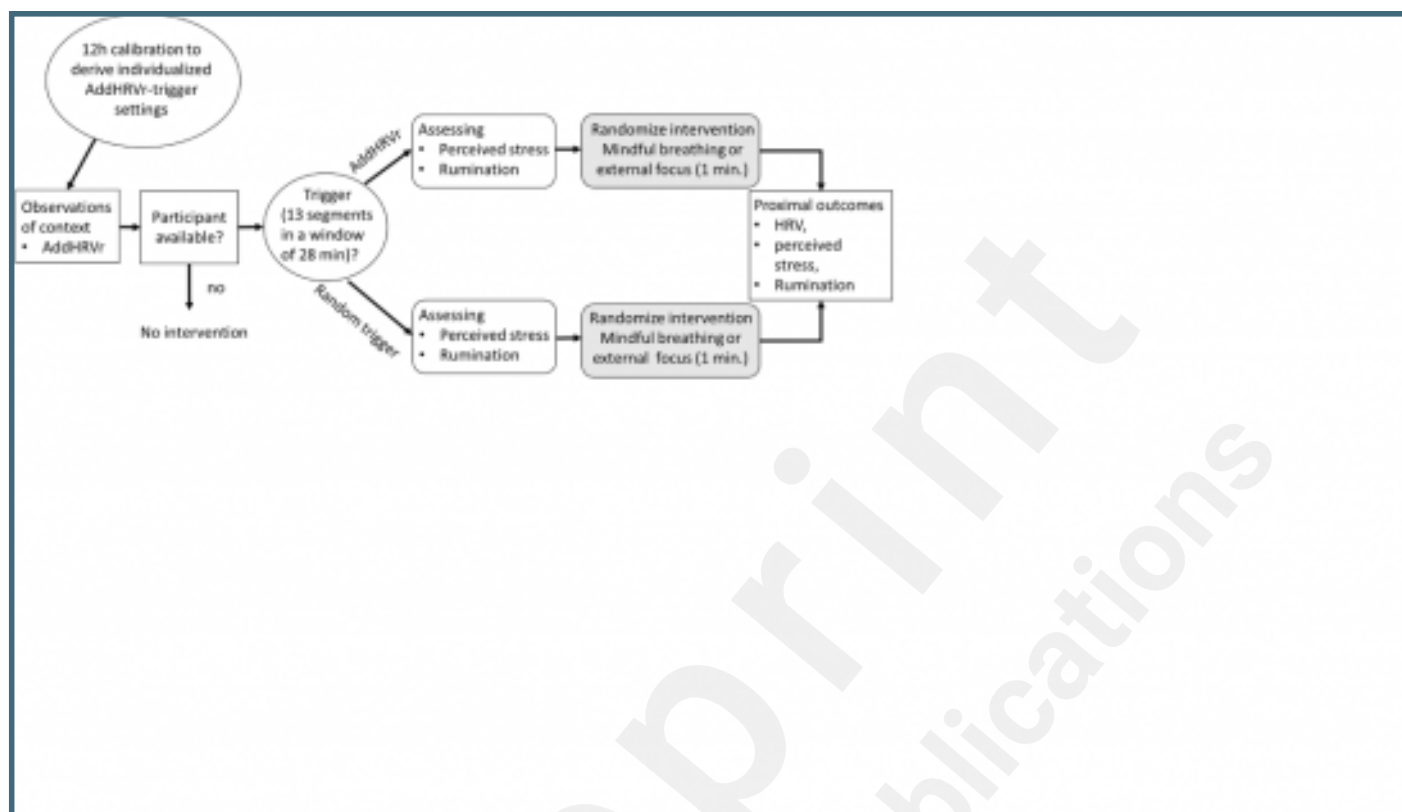


Fig. 3. App-based 0.1 Hz breathing intervention. Inhalation (“Einatmen”) was paced for 4 seconds and exhalation (“Ausatmen”) for 6 seconds as guided by a progress bar.

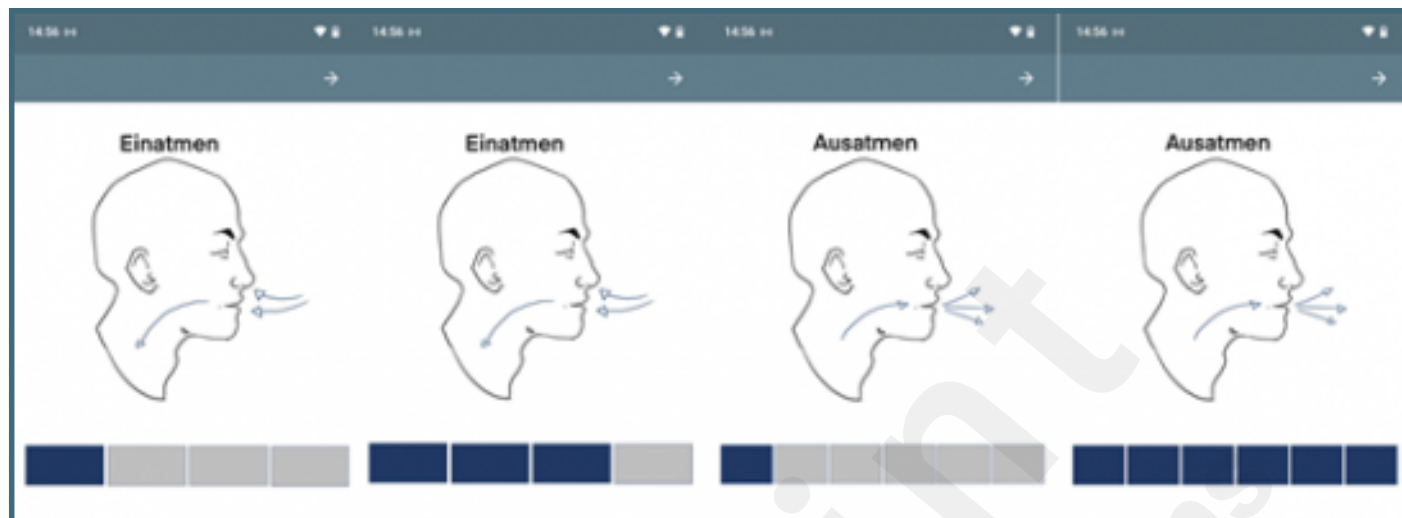


Fig. 4. Images and brief instructions of the app-based interventions, which were delivered following either AddHRVr- or random triggers. The mindful breathing intervention (left side) asked for directing attention towards mindful breathing, while the external attention task (right side) asked to focus attention toward a neutral object in the environment. Interventions were performed for 1 minute, randomized for trigger type.

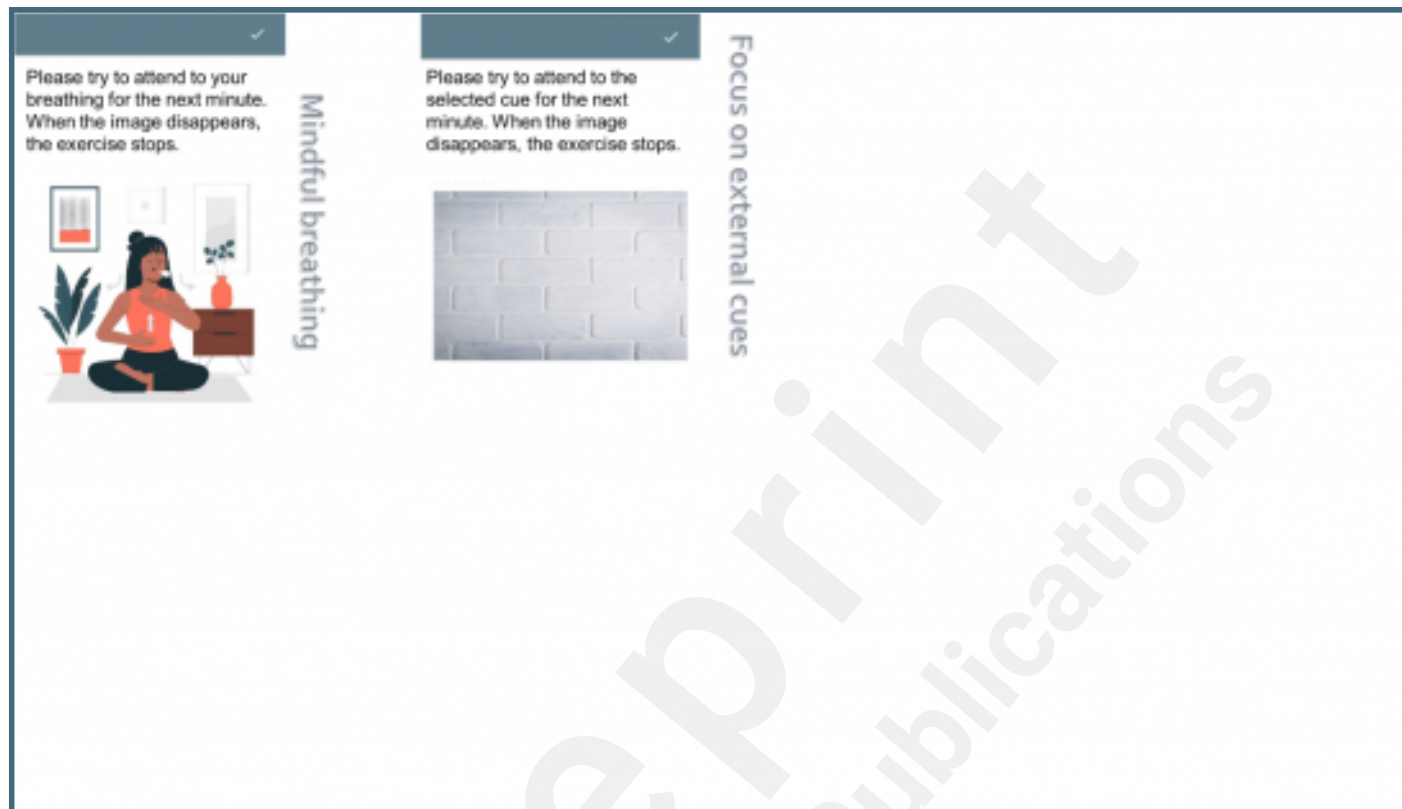


Fig. 5. Trajectories of vagally-mediated HRV (root mean squares of successive differences; RMSSD) 10 minutes before and after the prompt, respectively. The upper stippled line represents RMSSD following random prompts and the lower solid line indicates RMSSD following an AddHRVr-trigger. Stippled whiskers indicate 95% confidence intervals. Note, the shaded areas visualize the significant interaction between trigger and pre-post assessment and the stronger increase in RMSSD to the AddHRVr-triggered intervention is magnified on the right side.

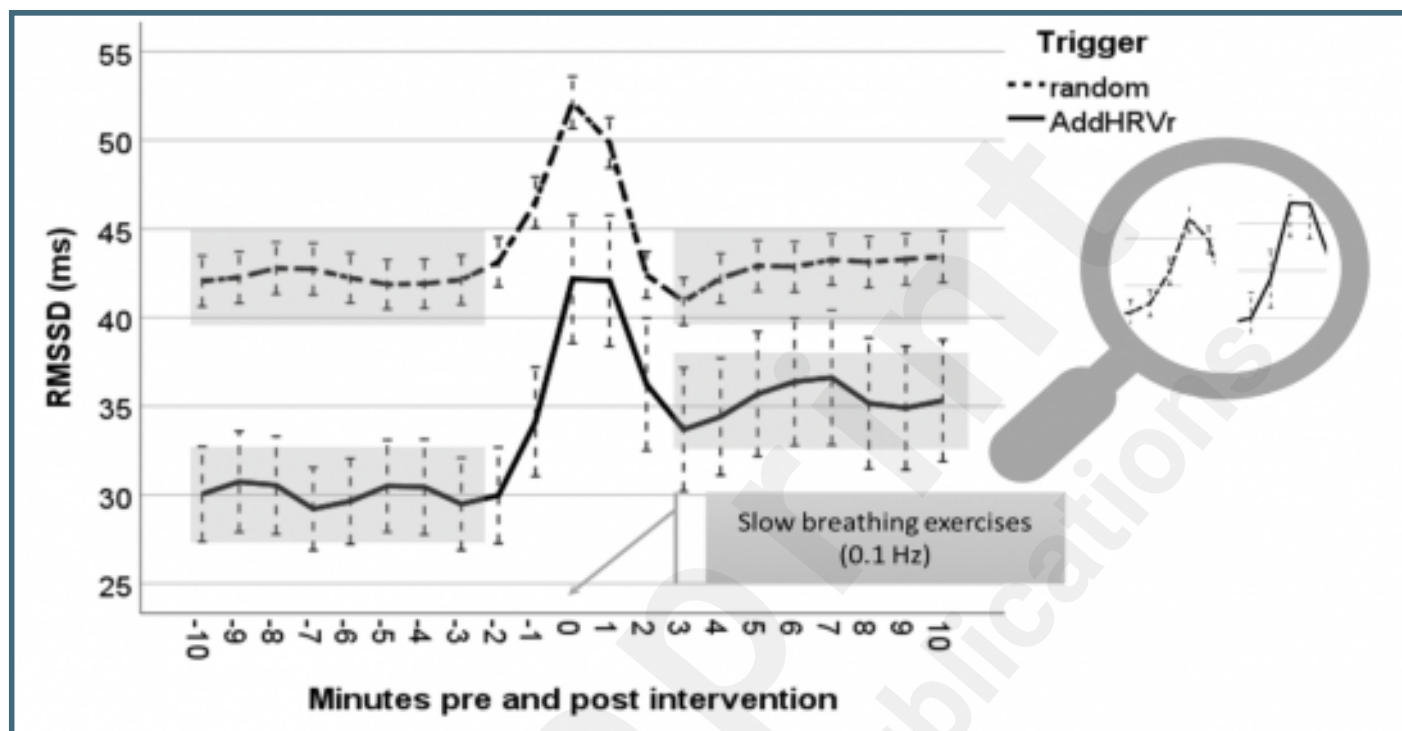
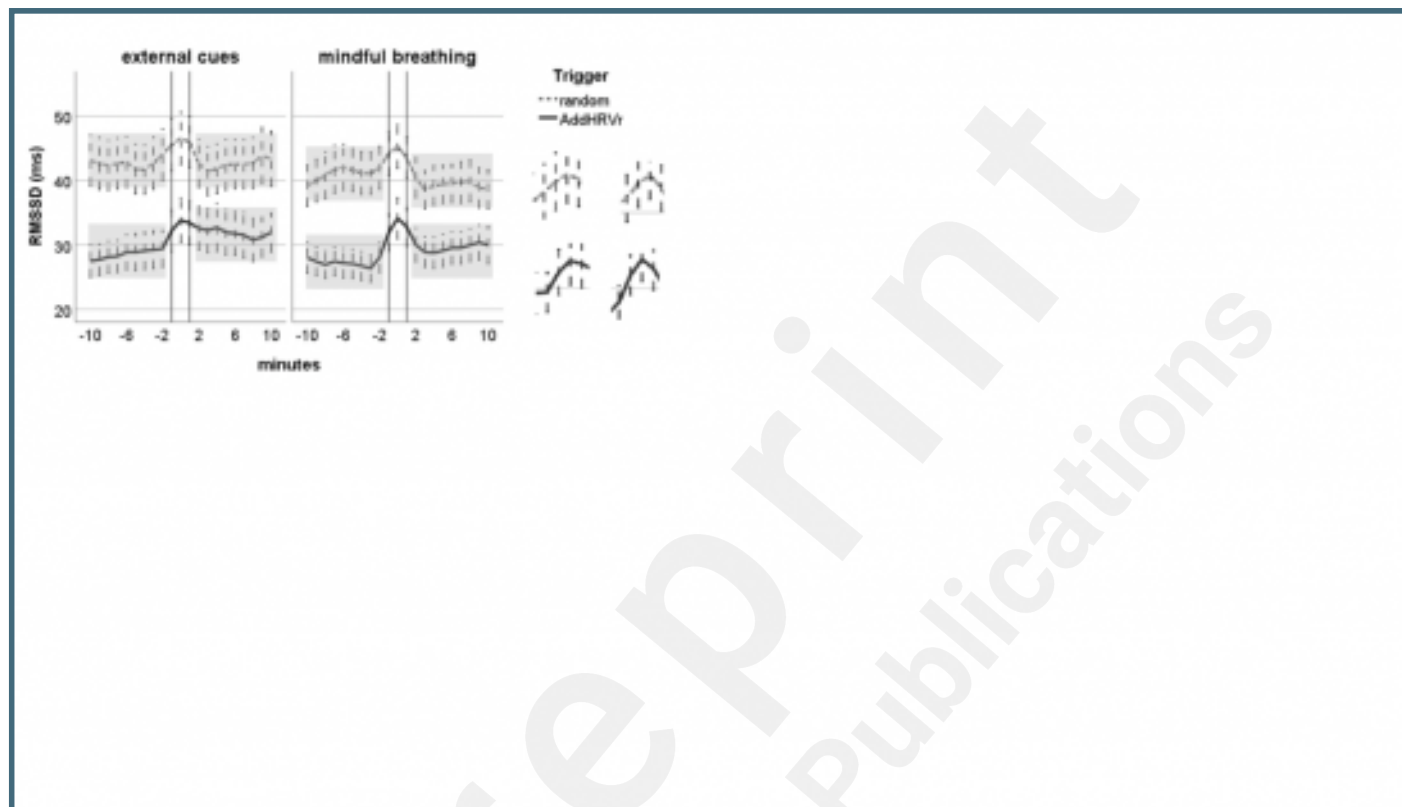


Fig. 6. Trajectories of vagally-mediated HRV (root mean squares of successive differences; RMSSD) 10 minutes before and after the prompt, respectively. The upper stippled line represents RMSSD following random prompts and the lower solid line indicates RMSSD following an AddHRVr-trigger. The external attention intervention (external cues) is depicted on the left side and the mindful breathing intervention on the right side. Stippled whiskers indicate 95% confidence intervals. Note, the shaded areas visualize the significant interaction between trigger and pre-post assessment and the stronger increases in RMSSD to the AddHRVr-triggered interventions are magnified on the right side.



Multimedia Appendixes

Fig. A1. Schematic representation of the individually adjusted AddHRVr algorithm based on RMSSD and bodily movement. Adapted with permission from Zeitschrift für Psychologie (2023), 231(4), 291–301. © 2023 Hogrefe Publishing www.hogrefe.com <https://doi.org/10.1027/2151-2604/a000537>.

URL: <http://asset.jmir.pub/assets/9f76790d4055f1fc0af3cb2f6cf79c49.docx>

Table A1. AddHRVr algorithm calibration parameters derived from 12h baseline recording in Study 1 and Study 2.

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Intervention instructions.

URL: <http://asset.jmir.pub/assets/d5baf82e9055b101cb2a2b2ba83c6094.docx>

Table A2. Multilevel regression predicting logarithmized RMSSD before (pre), during (intervention) and after the slow paced breathing intervention (post intervention) to three kind of triggers (virtual AddHRVr, random, AddHRVr). Note that Estimates refer to raw b-values (slopes) and CI to confidence intervals.

URL: <http://asset.jmir.pub/assets/94a35498561dde000785c6ff958b3c6b.docx>

Table A3. Multilevel regression predicting logarithmized RMSSD before (pre), during (intervention) and after intervention (post intervention) to three types of triggers (virtual AddHRVr, random, AddHRVr). Note that Estimates refer to raw b-values (slopes) and CI to confidence intervals.

URL: <http://asset.jmir.pub/assets/d647fb4267915523296bee27983a6ef9.docx>