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Efficacy of slow-paced breathing as a just-in-time adaptive intervention for anxiety – a randomized controlled study

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All authors contributed to the article. AML and TV formulated the research question and designed the analysis, which was performed by AML. AML obtained funding for the project and collected the data. TV, MH, and IMG supervised the project leading to these results. The first draft was written by AML, under the supervision of TV. All authors contributed to the revision. The authors have no conflict of interest to disclose.

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The hypotheses and analysis plan were postregistered. Postregistration, analysis code, and study materials are available on the OSF page: https://osf.io/q7mxd/. Data is not publicly available but can be requested via an abstract submission process.

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Abstract

Numerous studies have substantiated the efficacy of slow-paced breathing (SPB) in decreasing anxiety and increasing vagally-mediated heart rate variability (HRV). Given its effectiveness and simplicity, SPB is a promising candidate for a just-in-time adaptive intervention (JITAI). This study examined the efficacy of SPB, triggered by increased anxiety and perseverative cognition (PC), on reducing these symptoms and increasing HRV at macro, micro, and immediate levels. Eighty individuals with subclinical anxiety from the Flemish general population were randomized into experimental (EC) or passive control (CC) conditions. Anxiety symptoms were evaluated at baseline and after 15 days. Participants underwent a control period (CP; 6 days) and an intervention period (IP; 6 days), during which they reported momentary anxiety and PC via a mobile application while wearing a portable electrocardiogram. EC participants received SPB training between CP and IP and were prompted to use SPB exercises during IP when anxiety/PC increased. Analyses revealed a significant effect of SPB on reducing retrospectively reported anxiety ($p<.05$), but not on average daily-life anxiety and PC or HRV assessed throughout the IP. Micro-level analyses indicated that SPB was associated with a decrease in PC ($p<.05$) but not anxiety at the subsequent daily-life assessment. Anxiety and PC decreased substantially from immediately before to immediately after SPB (<.001). The effect of SPB on HRV remains inconclusive due to methodological concerns in measuring HRV in ambulatory settings. The results provide mixed evidence for the efficacy of SPB as a JITAI, indicating the need for replication studies to further evaluate its potential.

Keywords: slow breathing, just-in-time adaptive intervention, anxiety, perseverative cognition, heart rate variability

Introduction

Anxiety is characterized by dysregulation at multiple functional levels (Friedman, 2007). At the level of the Autonomic Nervous System (ANS), this dysregulation is exemplified by a trait-like withdrawal of cardiac vagal activity typically indexed by decreased heart rate variability (HRV; Tomasi et al., 2024). At a cognitive level, anxiety is associated with a tendency to engage in perseverative thinking (Friedman, 2007). Those perseverative cognitions (PC; worry and rumination) are considered key mechanisms for further maintaining emotional distress and physiological hyperarousal (Brosschot et al., 2006).

Considering that increased levels of anxiety are associated with a variety of adverse outcomes in terms of mental and physical health, including the development of clinical forms of anxiety (Bokma et al., 2020), other psychopathology (Jacobson & Newman, 2017), and higher mortality (Roest et al., 2010), timely interventions are crucial to prevent symptom exacerbation at early stages. While effective treatments exist (Black, 2006), epidemiological studies demonstrate that up to 80% of individuals meeting the diagnostic criteria for any anxiety disorder do not seek professional help (Bandelow & Michaelis, 2015). Alongside stigma and poor mental health literacy, relevant barriers to seeking help include high associated financial costs and limited access to mental health services (Andrade et al., 2014). Accordingly, there is an ever-increasing demand for interventions that are accessible and can be easily implemented in day-to-day settings, serving as either complementary treatments to gold-standard care or stand-alone interventions.

The rapid advancements of technology and the resulting high availability of mobile devices have paved the way for digital interventions, delivered remotely in the flow of one’s everyday life. Of particular interest are just-in-time-adaptive-interventions (JITAI’s) which are administered at predefined moments of risk, e.g., self-reporting increased levels of symptoms or changes in physiological state, allowing for a high degree of precision in targeting specific symptoms (Nahum-Shani et al., 2018). Intervening precisely at the onset of symptoms might be particularly effective as it can prevent further exacerbation of negative emotional states.

Indeed, over the past years, a number of digital interventions have been developed that target anxiety symptoms as either primary or secondary outcomes (Lu et al., 2022; Schueller et al., 2017). Typically, those interventions offer coping or emotion regulation strategies in the form of cognitive-behavioral therapy or psychoeducation. Meanwhile, considering the nature of anxiety with the underlying physiological dysregulation as a crucial feature (Friedman, 2007), anxious individuals could benefit from holistic JITAI's preventing the maintenance and exacerbation of anxiety and associated physiological hyperarousal. Such a JITAI could take the form of an intervention thought to regulate both ANS- and emotional functioning, namely slow-paced breathing (SPB; Laborde et al., 2022; Lehrer et al., 2020; Russo et al., 2017). SPB is a technique in which people voluntarily slow down their respiratory rate from approximately 10-20 breaths per minute (bpm) to about 6 bpm (i.e., the frequency of 0.1Hz) by following a breathing pacer. SPB at 6 bpm increases parameters of cardiac vagal control by inducing high amplitude oscillations in the heart (i.e., increasing vagally-mediated HRV), due to the coupling of two physiological rhythms – respiratory sinus arrhythmia and baroreflex responsible for blood-pressure regulation (Russo et al., 2017). One hypothesized mechanism of SPB's efficacy involves improving ANS functioning, via breathing-induced oscillations in the blood flow that cause a synchronized activation in the emotion regulation brain networks. Such repeated activity is thought to strengthen the functional connectivity within these brain regions (Mather & Thayer, 2018).

To date, several meta-analyses have demonstrated the effectiveness of SPB, in improving anxiety and related outcomes (Goessl et al., 2017; Lehrer et al, 2020; Leyro et al., 2021), while some have also shown evidence of its long-term efficacy in enhancing cardiac vagal control (Laborde et al., 2022). For instance, young adults reporting increased stress experienced significant reductions in worrying following 5 weeks of daily SPB exercises (de Bruin, 2016). Similarly, a 6-week SPB intervention resulted in reduced rumination and anxiety and increased vagally mediated HRV in depressed individuals (Schumann et al., 2022). Although a typical SPB protocol involves several weeks of training (Lehrer et al., 2013), laboratory studies have also demonstrated the immediate effects of SPB. For example, a single-session SPB effectively reduced state anxiety (Prinsloo et al., 2013), decreased mind wandering - a phenomenon closely linked with PC (Blum et al., 2019), and increased vagally mediated HRV (Magnon et al., 2021).

Collectively, these findings suggest that the SPB is a promising candidate for a JITAI, impacting both the momentary and longer-term outcomes. Notably, there is evidence linking the initially increased state level of anxiety to greater effectiveness of the intervention (Wells et al., 2012), suggesting that SPB intervention triggered at the moment of increased anxiety, thus as a JITAI, might be particularly beneficial. Moreover, SPB is characterized by high accessibility. Breathing exercises can be easily implemented remotely, at any location and time, and the availability of mobile breathing pacers renders this technique cost-effective or even cost-free. Likewise, a single training, paired with anti-hyperventilation instructions, is sufficient to learn the technique (Prinsloo et al., 2013; Szulczewski, 2019).

Although SPB emerges as a promising candidate for a JITAI, its efficacy in this form for treating anxiety is yet to be assessed. Whereas some studies have employed mobile applications to administer breathing exercises (Pham et al., 2016; Ponzo et al., 2020), none so far have tailored these to specific moments of risk (as is done in a JITAI). Likewise, despite the availability of commercial devices offering SPB exercises triggered based on physiological parameters (e.g., Fitbit), empirical evidence substantiating their efficacy is non-existent. Furthermore, no prior study attempted to monitor momentary changes in symptoms and physiology following SPB exercise completion in real-life settings to evaluate SPB's immediate effects.

Thus, the present study examines the efficacy of SPB as a JITAI triggered in response to increased self-reported symptoms in a 12-day randomized controlled trial (a six-day control period followed by either a six-day intervention period or a standard six-day observation period). The study uses experience sampling methodology (ESM) - a daily diary technique to assess momentary anxiety, momentary PC, and context (Myin-Germeys & Kuppens, 2022), paired with wearable electrocardiography (ECG) technology to measure HRV in real-time.

We test the efficacy of SPB triggered by self-reported anxiety or PC at three levels of temporal detail – macro (within a timeframe of days), micro (within a timeframe of hours), and immediate (within a timeframe of minutes). On the macro level, we examine its effects on anxiety symptoms reported after the intervention period, as well as on the average daily levels of anxiety and PC reported via ESM and average daily levels of HRV throughout the intervention period. On the micro level, we investigate the effect of SPB on anxiety and PC at the subsequent ESM assessment. Finally, at the immediate level, we analyze the immediate effects of SPB on anxiety, PC, and HRV, from immediately before to immediately after SPB.

At each level, we hypothesize that, compared to the control condition, engaging in SPB will be associated with a decrease in anxiety and PC, as well as with an increase in HRV.

Methods

Participants

The current study used data from the Daily Life Anxiety (DALIA) study, a single-blind randomized controlled trial in individuals from the general population reporting above-average levels of anxiety, conducted between September 2021 and June 2023 in Flanders, Belgium. Inclusion criteria involved being at least 18 years old and scoring ≥42 on the trait scale of the State-Trait Anxiety Inventory (STAI), corresponding to the 80th percentile among the Dutch-speaking population of students (Van der Ploeg, 2008). Exclusion criteria included a diagnosis of cardiovascular and/or respiratory disease, use of cardioactive medication, psychotherapeutic treatment for psychological complaints within the past two years, previous psychological treatment for anxiety, being familiar with the SPB technique, and practicing meditation/mindfulness/relaxation at least once a week. Written informed consent was obtained from all participants. The DALIA project was approved by the Ethics Committee Research UZ/KU Leuven (S65138).

Procedure

Screening and randomization

Data were collected using REDCap electronic data capture tools hosted at KU Leuven (Harris et al., 2009). Following the initial screening, participants were randomized into experimental or control conditions using a randomization module uploaded to the REDCap and underwent an interview with the Mini International Neuropsychiatric Interview (MINI; Lecrubier et al., 1997). The researcher conducting the interview (first author) was not blind to the condition, however, the data from the MINI were not used in any analyses and served solely to confirm the initial screening, i.e., to ensure the participants did not currently meet the diagnostic criteria for anxiety, depressive, or eating disorders. Likewise, considering that SPB is a behavioral intervention, the researcher could not remain blind to the condition. Nevertheless, the participants were unaware of the existence of the other condition, due to the use of separate versions of the informed consent form for each condition.

Baseline

Included participants were invited for the baseline lab visit, during which they provided demographic information (i.e., biological sex, age, ethnicity), completed a battery of questionnaires, and received a briefing regarding the ambulatory period of the study.

Control Period (CP)

The following day, participants commenced the initial six-day ambulatory period. We measured daily-life states using ESM in a semi-randomized sampling scheme, with notifications sent 10 times a day, within 90-minute intervals via the m-Path app (Mestdagh et al., 2023). The starting point for the questionnaires was individually determined for each participant and day, to ensure they were prompted during their waking hours. Questionnaires had a 15-minute expiration period. The items are available on the OSF website: https://osf.io/q7mxd/.

Simultaneously, participants wore an ambulatory chest-worn ECG monitoring device for continuous recording of ECG data during the six days (Health Patch, IMEC, Belgium) at a sampling frequency of 256 Hz (Smets, et al., 2018). Additionally, the device recorded acceleration data (ACC) with a 3-axis accelerometer at a sampling frequency of 32 Hz to assess movement. Participants were instructed to wear the device continuously, removing it only during intense physical activity, contact sports, swimming, or in case of skin irritation.

Slow-paced breathing training

After CP, participants were invited to the lab, where those in the control condition watched a neutral documentary for 30 minutes, while participants in the experimental condition underwent SPB training.

SPB training utilized the Elite HRV application (https://elitehrv.com/) and a CorSense photoplethysmography (PPG) sensor (Elite HRV. 2019. CorSense Heart Rate Variability. Webpage. https://elitehrv.com/corsense). A brief protocol for the SPB training was developed based on Lehrer et al.'s (2013) HRV biofeedback training protocol. Participants received information about HRV and its relation to psychological and physical health. Next, they were presented with an Elite HRV application displaying a breathing pacer set at the frequency of 6 bpm and a depiction of their pulse rate variability (i.e., a proxy of HRV). The inhalation and exhalation periods lasted, respectively, 4 and 6 seconds to maximize increases in HRV. Participants received anti-hyperventilation instruction and were trained in breathing in through the nose and out through pursed lips, and in diaphragmatic breathing. The training lasted approximately 30-40 minutes depending on how efficiently participants learned the technique.

Intervention Period (IP) and SPB as a JITAI

The second 6-day ambulatory assessment was identical to CP, except for an engagement in SPB in the experimental group. Participants were prompted through the mPath app to perform a 2-minute SPB exercise using the CorSense sensor and EliteHRV application. The prompts were sent when participants i) rated their momentary anxiety ≥ 3 (i.e., mild to moderate anxiety), on a scale from 1 to 7 or ii) indicated the presence of PC by reporting being distracted by their thoughts ≥ 2, on a scale from 1 to 7. At each prompt, participants could refuse the request. In the case of engaging in an SPB exercise, they were further instructed to initiate a questionnaire in m-Path immediately following the exercise, to report momentary anxiety, PC, and their perceived ability to follow the breathing pacer.

In addition, participants were instructed to self-initiate an SPB exercise three times a day at chosen moments and complete a follow-up self-initiated questionnaire in m-Path. In the macro-level analyses, we included all instances of completed SPB exercises, while micro-level analyses focused solely on those prompted by the ESM reports of increased anxiety and PC.

Post-measurement

One day after finalizing the IP, participants completed the same battery of questionnaires that were administered at baseline.

Measures

Anxiety symptoms

Anxiety symptoms were assessed at baseline and post-measurement with the Dutch version of the Beck Anxiety Inventory (BAI-NL) consisting of 21 items (Beck et al., 1993). Participants indicated how much they were bothered by each symptom a) in the past month (when asked at baseline) and b) during the IP (when asked at post-measurement). The answer options included: "Not at all" (0); "Mildly but it did not bother me much" (1); "Moderately - it was very unpleasant, but I could tolerate it" (2); "Severe; I could hardly bear it" (3). Anxiety symptoms score is the sum of ratings given by the participants to all questions (range 0-63). The reliability of BAI-NL, expressed in Cronbach's alpha, equaled α=.84 at baseline and α=.83 at post-measurement.

ESM-based variables

State anxiety. State anxiety was measured using the items from the Dutch version of the short STAI scale (Van der Bij et al., 2003). One item of the scale, namely "I feel worried", was omitted, as it is part of the PC construct which was assessed separately in this study. State anxiety was computed as the mean of the following five items, rated on a 7-point Likert scale from 1 (not at all) to 7 (very much): "At the moment, I feel tense/ upset/calm/relaxed/satisfied". The three last items were reverse-coded. The within-person and between-person internal consistency reflected in Cronbach's alphas corresponded to α=0.87 and α=0.87, respectively.

State PC. State PC was measured using conditional questions. Participants rated the statement "At the moment, I am distracted by my thoughts (i.e., worries, problems, memories)" on a 7-point Likert scale ranging from "1" (not at all) to "7" (very much). When the answer was higher than "1" (not at all), participants received the following items: "The same thoughts keep going through my mind again and again" (repetitiveness); "Thoughts come to my mind without me wanting them to" (intrusiveness); "I get stuck on certain issues and can't move on" (the feeling of being stuck). All items were rated on a Likert scale ranging from "1" (not at all) to "7" (very much). State PC was computed as the mean of these four items. The items have been validated and used in previous studies (Schettino et al., 2021). The within-person and between-person internal consistency reflected in Cronbach's alphas corresponded to, respectively, α= 0.83 and, α=0.85

Contextual variables. Several contextual variables were assessed using ESM.

Stressful events. Stressful events were reported using an item "Think of the most important event since the last beep. This event was…", rated on a 7-point bipolar scale ranging from "-3" (very unpleasant) to "3" (very pleasant)" with "0" as a neutral point. Scores "-3", "-2" and "-1" were recoded to "1" representing the presence of a stressful event. Scores "0", "1", "2" and "3" were recoded to "0" to represent its absence.

Substance intake. Substance intake was measured using a single multiple-choice item *"Since the last beep, I have used...".* Answer options included 'Nothing', 'Caffeine', 'Nicotine', 'Alcohol', 'Medication', 'Cannabis', or 'Other drugs', and participants could select multiple options. We created a binary variable indicating the intake of substances affecting heart rate, with "nothing" coded as "0", and "1" for any other response option.

Ability to follow the breathing pacer. The ability to follow the breathing pacer was measured using the item "Were you able to breathe in synchrony with the pacer?" rated on a 7-point Likert scale from 1 (not at all) to 7 (very much). This item was included in the self-initiated questionnaire which participants in the experimental condition completed after engaging in SPB.

Wearable-based variables

Heart Rate Variability. The quality assessment for the ECG signal was based on the work of Orphanidou et al. (2015), which showed a sensitivity of 94% and a specificity of 97% in artifact detection. Following their approach, we employed the following three rules: the extracted heart rate fell within the range of 40 to 180 beats per minute, the maximum gap between successive R-peaks was set at 3 seconds, and the beat-to-beat interval ratio within the segment was maintained at less than 2.2. All segments meeting these criteria were classified as either good or bad quality based on adaptive QRS template matching. The ECG parameters were averaged over the 2-minute time windows, and those with a quality indicator below 0.8 were excluded from the analysis following the approach of Smets et al. (2018).

HRV was assessed using the time and frequency domain measures of HRV. Within the time domain, we used the root mean square of successive RR interval differences (RMSSD) reflected in milliseconds. RMSSD reflects vagally-mediated HRV and is characterized by low sensitivity to changes in the respiratory rate, making it a suitable parameter for measuring parasympathetic influences in ambulatory settings when the respiratory rate is not always known (Penttilä et al., 2001). Additionally, we assessed the absolute power of the low-frequency (LF HRV) band (0.04–0.15 Hz) reflected in milliseconds squared (ms2). During slow breathing, when the respiration rate falls below 8.5 breaths per minute, vagally-mediated influences are primarily present in the LF band, resulting in an increase in LF HRV (Shaffer & Ginsberg, 2017). As a result, an increase in the LF power band may potentially serve as a proxy indicator of slow breathing. We analyzed i) RMSSD in 2-minute windows preceding each ESM notification, and ii) RMSSD and LF HRV in 2-minute windows immediately before, during, and immediately after SPB.

Movement. Movement was quantified using the mean of the accelerometer magnitude during the specified time windows of 2 minutes.

Data analysis

All analyses were conducted in R version 4.3.2 (R Core Team, 2023). Multilevel analyses were conducted using the 'lme' function from the 'nlme' package in R (Pinheiro et al., 2024), with restricted maximum likelihood estimation (REML) and listwise deletion for handling missing values.

Given the exploratory nature of the conducted analysis and the prior postregistration, controlling for multiple testing was not implemented, following the recommendations of Rothman (1990).

Macro-level effects of SPB

We tested the effect of the SPB on retrospectively-reported anxiety symptoms (H1a), using a linear regression analysis, with anxiety symptoms score at the post-measurement as an outcome, and condition (0=control; 1=experimental) as a predictor. The covariates included the total number of SPB exercises completed throughout the IP (n_SPB), anxiety symptoms reported at baseline, the total number of stressful events (n_stressors) reported in IP, ethnicity (0=Caucasian; 1=African; 2=Asian; 3=other) and sex (0=male; 1=female).

Next, to examine the effect of the intervention on average state levels of anxiety and PC across the intervention period, we fitted two linear mixed-effects models with state anxiety (H1b) or PC (H1c) reported during the IP as outcomes. In both models, the predictor was the condition and fixed effects covariates included the person-mean level of, respectively, state anxiety or PC measured throughout the CP, n_stressors in IP, n_SPB, sex, and ethnicity. Likewise, to examine the effect of the intervention on average HRV (H1d), we fitted a linear mixed-effects model with average RMSSD over 2-minute time-windows preceding each ESM assessment during the IP as outcome. The predictors were: condition, person-mean RMSSD in CP, mean ACC in 2-minute time windows before each ESM assessment in IP, n_stressors in IP, n_SPB, substance intake at each ESM assessment (0=none; 1=any substance), age, ethnicity, and sex. Random intercepts were included for participants' unique id’s, along with an exponential serial autocorrelation structure to address potential temporal dependencies in models H1b, H1c, and H1d. Because of the expected correlation between the condition and the number of completed exercises, we used the Variance Inflation Factor (VIF) to assess potential multicollinearity in the models showing significant associations.

Micro-level effects of SPB

To examine the effect of SPB on the micro level, we used only data from the IP. Further, we preselected the following subset of the data for the analysis: in the experimental condition, we included only ESM assessments followed by an SPB as a JITAI (t_0; n=616), as well as the closest non-missing ESM assessment (t_{+n}). In the control condition, we included ESM assessments where state anxiety ≥3 or state PC ≥2 (t_0; n=1270), as well as the next completed ESM assessment (t_{+n}). On this data subset, we fitted two linear mixed-effects models with, respectively, state anxiety (H2a) and PC (H2b) at t_{+n} as outcome and condition and the person-mean centered state anxiety or PC (respectively) as predictors. Next, in a follow-up analysis, we repeated the two models H2a and H2b after including the respective interaction terms - condition*person-mean centered state anxiety (H2c), and condition*person-mean centered state PC (H2d). The fixed effects covariates in all four models included minutes elapsed between t_0 and t_{+n} and reported stressful events (0=no event; 1=event) at t_{+n}.

To account for the nested structure of the data in all four models, we specified a random slope for person-mean centered anxiety or PC, and a random intercept for participants' unique id, reflecting the nested nature of observations within each participant.

Immediate-level effects of SPB

The immediate effects of SPB were tested in a non-randomized design, within the experimental condition. We preselected time points where SPB was triggered as a JITAI and followed by the self-initiated ESM questionnaire (n=635). We fitted two linear mixed-effects models with, respectively, state anxiety (H3a) and PC (H3b) as outcomes. In both models, the predictors were a binary variable timepoint (0=before SPB; 1=after SPB), and a continuous variable reflecting the ability to follow the breathing pacer (pacer_SPB) as a covariate.

Likewise, to examine the immediate effects of SPB on HRV (H3c), we used linear mixed-effects models in the experimental group with two parameters of HRV measured in 2-minute windows (i.e., RMSSD, LF HRV) as the outcomes. LF HRV values were log-transformed to satisfy the normality assumption. We fitted one model per parameter, with a three-level categorical variable timepoint (0=before; 1=during; 2=after) as a predictor. Both models included the following covariates: substance intake reported immediately before the SPB and the mean ACC value in each 2-minute time window. A random intercept was specified for participants' unique ID in all models.

Transparency and Openness

Data are not publicly available, however, can be requested via an abstract submission process. The hypotheses and analysis plan were postregistered. The postregistration, transparent changes to postregistartion, analysis code, and ESM items are available on the OSF page: https://osf.io/q7mxd/. The BAI questionnaire can be found using the provided reference.

Results

Descriptive statistics

The sample comprised n=40 participants in the control and n=40 participants in the experimental conditions. There were no significant differences between the conditions in terms of sex, age, ethnicity, or retrospectively reported anxiety symptoms at both, baseline and post-measurement (p>.05). Likewise, no significant differences were found in state anxiety, state PC, RMSSD, or the number of reported stressors in CP or IP (p>.05). Participants in the experimental condition were prompted to engage in SPB as a JITAI a total of n=1,404 times, with a mean compliance rate of 52.99% (n=744). Descriptive statistics are presented in Table 1. Descriptive statistics for anxiety, PC, and HRV at the immediate level of the analysis are available in Supplementary Materials 1 and 2.

Macro-level effects of SPB

Anxiety symptoms

Results of the linear regression analysis showed no significant effect of the condition (p>.05) but did reveal a significant positive association between the number of completed SPB exercises, and anxiety symptoms at post-measurement (p<.05). Completing more SPB exercises was associated with a lower level of anxiety symptoms, indicating of a dose-response association. The Variance Inflation Factor (VIF) indicated no concerns regarding multicollinearity for these two predictors (condition, VIF=3.19; n_SPB, VIF=3.17). Additionally, anxiety symptoms at post-measurement were positively associated with anxiety symptoms at baseline and female sex ($p<.05$), but not with the number of stressors in IP and ethnicity ($p>.05$).

Average state levels of anxiety, PC, and HRV

Macro-level daily-life analyses revealed no effect of SPB on average state levels of state anxiety, state PC, and RMSSD in IP. We observed no effect of the condition nor the number of completed SPB exercises in any of the models (H1b, H1c, H1d; $p>.05$).

In model H1b, the total number of stressful events reported in IP, and mean levels of state anxiety from CP were positively associated with the state anxiety in IP ($p<.001$). Sex and ethnicity showed no significant relationship with the outcome ($p>.05$). Likewise, in model H1b, state PC reported in IP was positively associated with the total number of stressful events reported in IP, and mean levels of state PC from CP ($p<.001$), but not with sex and ethnicity ($p>.05$). In model H1d, mean levels of RMSDD from CP were positively associated with RMSSD in IP. No significant associations were found between RMSSD and the total number of stressful events reported in IP, ACC, substance intake at each assessment, sex, ethnicity, and age ($p>.05$). Results are presented in Table 2.

Micro-level effects of SPB

State anxiety and state PC

We found no significant effect of condition in either of the models, suggesting no micro-level effect of SPB on state anxiety (H2a) and state PC (H2b).

In model H2a, we observed a positive autocorrelation, with state anxiety at t_0 predicting greater state anxiety and t_{+n} ($p<.001$). Additionally, reporting a stressful event at t_{+n} was positively linked with state anxiety at the same timepoint ($p<.001$), but not with minutes elapsed between t_0 and t_{+n} (p>.05). Likewise, in model H2b, the outcome, i.e., PC at t_{+n} was positively associated with PC at t_0 and reporting a stressful event at t_{+n} but not with minutes elapsed between t_0 and t_{+n} (p>.05). Results are presented in Table 3.

Follow-up analysis of the interaction effects

In model H2c, we found no significant effect of the condition*state anxiety at t_0 interaction on state anxiety. However, in model H2d, the condition*PC at t_0 interaction showed a significant negative association with state PC at t_{+n}, demonstrating that in the experimental condition, higher state PC scores at t_0 were associated with a lower state PC at t_{+n}. The interaction effects for models H2c and H2d are presented in Figure 1. Full results for models H2c and H2d are reported in Supplementary Materials 3, Table S3.

In addition, we performed a sensitivity analysis after excluding n=86 time points with a low reported ability to follow a breathing pacer (≤ 4 on a 7-point scale). The results confirmed the findings of the main analyses. Notably, we observed a marginally larger effect and a lower significance level of the condition*PC at t0 interaction (β=-0.171; *SE*=0.071; *CI*=[-0.311, -0.031]; *p*=.016), indicating that the effect of the SPB was greater when participants performed the exercise correctly. Results of the sensitivity analyses are reported in Supplementary Materials 4, Table 4.

Immediate-level effects of SPB

State anxiety and state PC

The within-experimental condition analysis demonstrated that engaging in SPB was strongly associated with a decrease in both state anxiety and state PC levels immediately following the exercise. We found a negative association between the timepoint identifying moments immediately following the intervention and state anxiety level (H3a; β=-0.444, *SE*=0.050; *p*<.001; CI=[-0.543, -0.346]). The same association was observed for state PC levels, where the timepoints reflecting the moments following SPB were associated with lower levels of state

PC as compared with the moments immediately preceding SPB (H3b; -0.451, *SE*=0.066; *p*<.001; CI=[-0.581, -0.322]). In both models, the ability to follow a breathing pacer was negatively associated with, respectively, state anxiety (β=-0.11, *SE*=0.023; *p*<.001; CI=[-0.156, -0.667]), and state PC (β=-0.090, *SE*=0.030; *p*=.003; CI=[-0.148, -0.031]).

HRV

The within-experimental condition analyses revealed significant although unexpected effects of SPB on HRV. In the RMSSD model, both, the timepoint reflecting a 2-minute window during SPB and immediately following SPB were associated with lower RMSSD as compared to the timepoint immediately preceding SPB (<.001), which suggests that engaging in SPB led to a decrease in parasympathetic activity. Additionally, the outcome was negatively associated with the ACC level (p<.05), but not with confounders, or the ability to follow the breathing pacer (p>.05).

The analysis on log-transformed LF HRV demonstrated that the timepoint reflecting a 2-minute window during SPB was linked to a substantial increase in the LF power band, in line with the expectations (p<.001). The timepoint reflecting a 2-minute window immediately following SPB was not associated with the outcome (p>.05). We found no significant effects of confounders, ACC, and the ability to follow the breathing pacer (p<.05).

Discussion

The current study is the first to examine the effect of an SPB in the form of a JITAI on average and momentary levels of anxiety, PC, and HRV. Our results indicated no significant effects of the condition on anxiety symptoms, although a significant effect of the total number of SPB exercises was found. No significant effects of either condition or number of SPB exercises were observed on average daily-life state anxiety, PC, or HRV throughout the intervention period. At the micro-level, engaging in SPB was associated with a reduction in PC, particularly at moments with initially high perseveration, yet no such association was found for anxiety. The immediate-level analyses revealed that the levels of both anxiety and PC were significantly lower at moments immediately following, as compared to immediately preceding SPB. The effect of SPB on macro- and micro-level HRV was not confirmed.

Effects of the intervention on anxiety and PC

Although we found no significant effect of condition on the change in retrospectively reported anxiety symptoms, we observed a dose-response relationship, indicating a linear negative relationship between the number of completed SPB exercises and anxiety symptoms. These findings suggest that the intervention was effective in decreasing anxiety symptoms only in individuals who practiced more frequently, which is understandable given the large variability in the number of completed SPB exercises (ranging from 5 to 47). Possibly, the average number of completed exercises was too low to result in a decrease in symptoms. Indeed, a recent review highlighted a significant dose-response effect of JITAI's on the reduction in anxiety symptoms, albeit the dose-response referred to the duration of the intervention period rather than the number of completed JITAI's (Lu et al., 2022). Moreover, since JITAI prompts were triggered in response to increased symptoms, those who engaged in SPB more frequently might have had greater potential for symptom improvement, which could explain the observed dose-response effect.

Contrary to expectations, we did not find significant group differences between conditions regarding average state levels of anxiety and PC throughout the intervention period, indicating no effect of SPB on symptoms assessed in daily life. Likewise, the number of completed SPB exercises did not predict average state levels of anxiety and PC, in contrast to the result observed for retrospectively reported symptoms. Although the disparity in findings is unexpected, it is possible that participants recalled their symptoms differently when reflecting on the entire week, and these ratings might not have aligned with the day-to-day measures, as evidenced in prior research (Sato & Kawahara, 2011; Van Den Bergh & Walentynowicz, 2016). Thus, we cannot reject the possibility that the discrepancy between questionnaire- and ESM-based results may stem from retrospective bias in symptom reporting.

At the micro-level, we found no direct effect of the condition on the level of state PC or anxiety at the assessment following the SPB. However, we did observe a change in the perseverative thinking pattern in the experimental condition arguably signifying enhanced recovery from perseveration (Scheffer et al., 2018). Specifically, a significant interaction effect suggests that in those who completed the SPB exercises, a higher level of PC at the moment of initiation of the intervention was linked with a greater decrease in PC at the following assessment. This finding suggests that SPB had a distinct impact on disrupting the persistence of PC and was most effective when individuals experienced high levels of perseveration, likely due to more potential for improvement during those periods. Moreover, the immediate-level analyses within the experimental condition demonstrated significant substantial reductions in both state anxiety and PC immediately following SPB. These findings mirror those observed in laboratory settings (Blum et al., 2019; Magnon et al., 2021; Prinsloo et al., 2013), and suggest an immediate effect of SPB on momentary anxiety and PC, although the fact that we don't find effects on next-moment ESM assessments suggest that, at least for anxiety, they do not persist over time. Nonetheless, it is imperative to interpret these findings with a high degree of caution, given the absence of a control condition at this level of analysis.

Effects of the intervention on HRV

The macro-level analyses demonstrated no effect of condition or number of completed SPB exercises on RMSSD across the intervention week. While these results contradict some of the existing literature (for a review see: Laborde et al., 2022), we must acknowledge that previous studies assessed HRV in controlled laboratory settings, whereas in this study HRV was measured in ambulatory conditions. Consequently, direct comparisons may be limited due to measurement discrepancies between those two conditions. In the micro-level analyses, we found an approximately fourfold increase in LF HRV during SPB which might suggest a successful execution of the breathing exercise (Shaffer & Ginsberg, 2017). Nevertheless, a direct comparison of LF HRV before, during, and after SPB is not feasible, given that when respiratory frequency falls outside of the slow-breathing spectrum (i.e., above 8.5 breaths per minute), LF HRV may reflect both parasympathetic and sympathetic influences (Shaffer & Ginsberg, 2017). Consequently, concluding changes in parasympathetic activation based solely on LF HRV is not possible. Unexpectedly, contrary to our hypotheses and prior literature (Laborde et al., 2022; Lehrer et al., 2020), we found a significant decrease in RMSSD both, during and after SPB relative to the moment before, suggesting a reduction in parasympathetic activation. Despite being instructed to avoid deep breathing, participants may have induced hyperventilation, leading to increased sympathetic and decreased parasympathetic activity (Spiesshoefer et al., 2019). Concurrently, the consistently high ratings of ability to follow the breathing pacer suggest that participants successfully maintained the breathing frequency of 6 breaths per minute. While this could imply that participants were able to increase parasympathetic activity during SPB exercise, the RMSSD findings do not support this speculation.

Nevertheless, the observed decreases in RMSSD were likely driven by other factors. Previous research demonstrated a differential activation of the autonomic nervous system during sitting and standing (Grosprêtre et al., 2021), and showed that movement might obstruct the accurate assessment of HRV parameters (Porges et al., 2007). Considering that the intervention took place in daily-life settings, we were unable to satisfactorily control for participants’ posture or movement, likely introducing noise into the data and precluding accurate detection of breathing-related HRV changes. Thus, the challenges inherent in ambulatory HRV measurement preclude definitive conclusions regarding the modulation of parasympathetic activity during SPB. We recommend that both the long- and short-term effects of SPB on HRV be assessed in controlled conditions to accurately address potential confounding factors.

Limitations and future directions

The present study represents the first attempt to employ SPB as a JITAI while monitoring its effects on daily-life levels of anxiety, PC, and HRV. This research might help inform more complex applications of SPB within the JITAI framework, such as those triggered in response to changes in physiological state (Schwerdtfeger & Ofner, 2023). Moreover, it adds to the existing slow-breathing literature, by examining the impact of SPB not only on retrospectively assessed symptoms but also on dynamic states throughout daily life. However, several limitations of the present study should be addressed.

Importantly, the passive nature of the control condition obstructs the isolation of SPB’s effect from potential other effects. For instance, simply focusing on one’s breath without changing the breathing frequency was linked to reduced reactivity to the repetitive thoughts (Feldman et al., 2010), and a decrease in their intrusiveness (Wu et al., 2023) due to distraction. We cannot reject the possibility that this mechanism contributed to SPB's effectiveness in reducing PC on a momentary level. Future studies should incorporate active control conditions encompassing relaxation techniques, as well as breathing at various respiratory rates. Furthermore, the effect sizes were small and significance levels were not robust, highlighting the need for replication. Additionally, assuming the effectiveness of the intervention, completion of the SPB intervention inherently decreases intervention triggers. Consequently, capturing the effect of SPB in the current setup is somewhat limited. Likewise, it remains plausible that participants may have ignored ESM notifications during periods of increased anxiety, missing intervention triggers when they could have been most beneficial in preventing symptom exacerbation. Moreover, the effectiveness of the intervention might have been affected by its perceived burden, causing reduced engagement. We did not set a maximum number of triggers for SPB exercises per day, thus the intervention might have been triggered too frequently leading to intervention fatigue (Nahum-Shani et al., 2018). Further research should implement personalized thresholds, to mitigate this risk, and explore the possibility of using passive sensing to trigger JITAIs in the most convenient situational context. Finally, the generalizability of the findings might be limited by the predominance of young females in our sample. This issue should be addressed in future studies to assess the effectiveness of SPB across diverse populations.

Conclusions

The current study provides mixed evidence for the efficacy of SPB as a JITAI for anxiety. The findings demonstrate that engaging in SPB throughout an individual's daily life alleviates anxiety symptoms, however, the dose-response relationship encompassed both the SPB triggered by symptoms increases (i.e., as a JITAI) and self-initiated SPB exercises. Moreover, although completing the SPB exercise was linked with an immediate decrease in both anxiety and PC, these effects did not persist over time, except for a reduction in perseveration at the moments of initially high PC. Although this finding suggests the potential of SPB in the form of the JITAI to interrupt the persistence of perseverative thinking, it remains unclear whether this mechanism is specific to SPB or merely reflects a distraction from current thoughts. Finally, the inconclusive findings concerning HRV underscore the challenges inherent in measuring the physiological effects of SPB in ambulatory settings.

Further replication with active control conditions is imperative to validate our findings. Additionally, future research should enhance precision and personalization in intervention delivery to improve efficacy and mitigate potential JITAI-specific fatigue.

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Table 1.
Socio-demographic data and descriptive statistics for the control and experimental conditions.

	Full sample (N=80)		
	Experimental (n=40)	**Control (n=40)**	
	***M* (*SD*), range / n (%)**	***M* (*SD*), range / n (%)**	***t/χ2***
Age	21.78 (8.21), 18-58	21.03 (4.06), 18-36	*t*=-0.52
Sex (female)	31 (77.50%)	33 (82.50 %)	*χ2=0.31*
Ethnicity			
Caucasian	30 (75.00%)	33 (82.50%)	*χ2=0.79*
African	5 (12.50%)	4 (10.00%)	
Asian	3 (7.50%)	2 (5.00%)	
Other	2 (5.00%)	1 (2.50%)	
BAI			
Baseline	18.15 (7.80), 2-37	16.18 (8.73), 3-41	*t* =-1.07
Post-measurement	16.10 (7.08), 1-32	17.10 (8.23), 4-37	*t*=0.58
State anxiety			
Control Period	3.49 (0.54), 2.10-4.50	3.50 (0.60), 2.4-5.34	*t*=0.10
Intervention Period	3.27 (0.57), 1.71-4.39	3.35 (0.76), 1.98-5.05	*t*=0.48
State PC			
Control Period	3.07 (0.83), 1.23-4.78	2.83 (1.00), 1.15-5.61	*t*=-1.18
Intervention Period	2.86 (0.94), 1.03-4.87	2.77 (1.23), 1.55	*t*=-0.36
Number of stressors			
Control Period	15.13 (6.92), 3-37	13.83 (7.19), 3-38	*t* =-0.82
Intervention Period	10.53 (7.23), 1-32	11.50 (8.13), 0-41	*t*=0.57
RMSSD in a 2-minute window			
Control Period	74.763 (26.24), 35.09-128.03	71.06 (16.57), 44.00-115.61	*t*=-0.53
Intervention Period	71.20 (18.25), 50.70-117.83	68.82 (15.28), 39.03-93.28	*t*=-0.40
Number of SPB interventions			
SPB as a JITAI	18.60 (10.84), 2-44	NA	NA
Including self-initiated SPB	21.93 (10.44), 5-47		
Number of prompts for SPB as a JITAI	39.60 (10.57), 7-54	NA	NA
Self-reported ability to follow the breathing pacer	5.50 (0.73), 3.8-6.8	NA	NA

Note. *M(SD)*=mean (standard deviation); n (%)=frequencies (percentage); BAI – Beck Anxiety Inventory; SPB=slow-paced breathing; RMSSD=root mean square of successive differences; JITAI=just-in-time adaptive intervention; NA=not applicable; *=$p<.05$.

Table 2.

Results of macro-level analyses, including one linear regression analysis of SPB's effect on retrospectively assessed anxiety symptoms (H1a), and three mixed-effects analyses of SPB's effect on state anxiety (H1b), state PC (H1c), and RMSSD (H1d).

Outcome	Predictors	*β*	*SE*	*p*	*CI*
H1a					
BAI at post-measurement					
	Condition	1.247	2.203	0.573	[-3.148, 5.642]
	BAI at baseline	0.598	0.079	<.001*	[0.441, 0.756]
	Number of completed SPB exercises	-0.153	0.072	.038*	[-0.297, -0.008]
	Number of stressors in IP	0.151	0.081	.067	[-0.011, 0.313]
	Sex	3.891	1.592	.017*	[0.714, 7.068]
	Ethnicity				
	African	2.292	1.993	.254	[-1.684, 6.268]
	Asian	0.789	2.564	.759	[-4.326, 5.904]
	Other	5.324	3.302	.111	[-1.264, 11.913]
H1b					
State anxiety					
	Condition	0.001	0.153	.996	[-0.305, 0.307]
	Mean anxiety from CP	0.838	0.086	>.001*	[0.667, 1.009]
	Number of completed SPB exercises	-0.002	0.005	.731	[-0.012, 0.008]
	Number of stressors in IP	0.022	0.006	.001*	[0.009, 0.035]
	Sex	0.079	0.109	.475	[-0.140, 0.297]
	Ethnicity				
	African	0.207	0.151	.175	[-0.094, 0.508]
	Asian	-0.025	0.179	.890	[-0.382, 0.332]
	Other	-0.048	0.232	.837	[-0.510, 0.414]
H1c					
State PC					
	Condition	0.020	0.261	.938	[-0.501, 0.542]
	Mean PC from CP	0.873	0.084	>.001*	[0.706, 1.040]
	Number of completed SPB exercises	-0.004	0.009	.671	[-0.021, 0.013]
	Number of stressors in IP	0.029	0.010	.006*	[0.009, 0.049]
	Sex	0.152	0.187	.418	[-0.220, 0.524]
	Ethnicity				
	African	0.256	0.255	.318	[-0.252, 0.765]
	Asian	-0.413	0.306	.182	[-1.024, 0.198]
	Other	-0.091	0.396	.819	[-0.881, 0.699]
H1d					
RMSSD					
	Condition	-2.703	10.366	.797	[-24.260, 18.853]
	Mean RMSSD from CP	0.696	0.140	<.001*	[0.406, 0.987]
	Number of completed SPB exercises	0.003	0.275	.992	[-0.568, 0.574]

Number of stressors in IP	-0.052	0.362	.886	[-0.805, 0.700]
ACC	-434.601	530.510	.413	[-1476.136, 606.935]
Substance intake	2.857	4.079	.484	[-5.152, 10.866]
Age	-0.606	0.773	.442	[-2.214, 1.002]
Sex	0.211	7.181	.977	[-14.723, 15.146]
Ethnicity				
African	-5.268	7.296	.478	[-20.441, 9.906]
Asian	-13.889	14.439	.347	[-43.916, 16.139]
Other	-15.213	14.665	.311	[-45.711, 15.285]

Note. SPB=slow-paced breathing; BAI – Beck Anxiety Inventory; CP=Control Period; IP=Intervention Period; PC=perseverative cognition; ACC=accelerometer data; RMSSD=root mean square of successive differences; ethnicity reference level=Caucasian; *=$p<.05$.

Table 3

Results of the micro-level analysis from two mixed-effects models assessing the effect of SPB on state anxiety (H2a) and state PC (H2b) at the following ESM assessment.

Outcome	**Predictors**	***β***	***SE***	***p***	***CI***
H2a					
State anxiety at the following assessment					
	Condition	-0.137	0.127	.284	[-0.391, 0.116]
	State anxiety at t_0	0.205	0.030	<.001*	[0.145, 0.265]
	Stressor reported at the following assessment	1.105	0.054	<.001*	[0.999, 1.210]
	Minutes elapsed between two assessments	0.000	0.000	.503	[-0.001, 0.000]
H2b					
State PC at the following assessment					
	Condition	0.021	0.245	.932	[-0.467, 0.509]
	State PC at t_0	0.189	0.036	<.001*	[0.118, 0.259]
	Stressor reported at the following assessment	0.816	0.069	<.001*	[0.680, 0.951]
	Minutes elapsed between two assessments	0.000	0.000	.553	[-0.001, 0.001]

Note. ESM=experience sampling method; SPB=slow-paced breathing; PC=perseverative cognition; t0=timepoint at which the initial level of state anxiety and state PC is measured; *=*p<.05*.

Table 4.

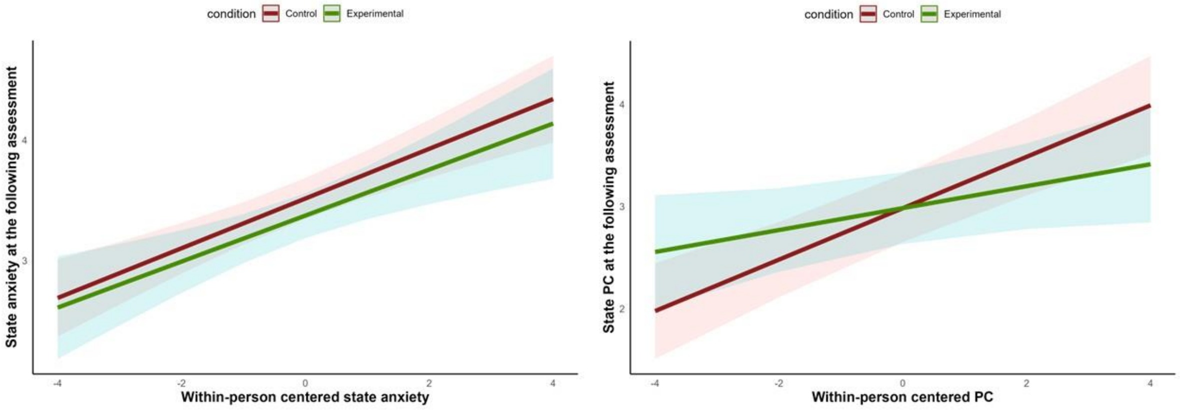
Results of two mixed-effects models assessing the immediate effects of SPB on RMSSD and log-transformed LF HRV (H3c).

Outcome	Predictors	*β*	*SE*	*p*	*CI*
RMSSD					
	During SPB	-11.042	2.547	<.001*	[-16.040, -6.044]
	After SPB	-16.138	2.703	<.001*	[-21.441, -10.836]
	ACC	-1612.155	548.017	.003*	[-2687.403, -536.906]
	Confounders	2.298	3.510	.513	[-4.589, 9.185]
	Ability to follow the breathing pacer	0.628	0.917	.493	[-1.171, 2.428]
LF HRV (log-transformed)					
	During SPB	1.581	0.060	<.001*	[1.463, 1.700]
	After SPB	-0.077	0.064	.231	[-0.203, 0.049]
	ACC	7.461	12.940	.564	[-17.928, 32.851]
	Confounders	0.137	0.083	.099	[-0.026, 0.200]
	Ability to follow the breathing pacer	0.037	0.022	.085	[-0.005, 0.080]

Note. SPB=slow-paced breathing; ACC=accelerometer data; RMSSD=root mean square of successive differences expressed in milliseconds (ms); LF HRV=log-transformed low-frequency heart rate variability expressed in millisecond squared (ms^2); reference level is, respectively, RMSSD or LF HRV in a 2-minute time window immediately preceding the SPB exercise; *=$p<.05$.

Figure 1

*Interaction effects of condition*state anxiety at t_0 (H2c), and condition*state PC at t_0 (H2d) on, respectively, state anxiety and state PC at the following assessment (t_{+n}).*



Note. PC=perseverative cognition