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Psychophysiological effects of slow-paced breathing at six cycles per minute with or without heart rate variability biofeedback

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Abstract

Heart rate variability (HRV) biofeedback, referring to slow-paced breathing (SPB) realized while visualizing a heart rate, HRV, and/or respiratory signal, has become an adjunct treatment for a large range of psychologic and medical conditions. However, the underlying mechanisms explaining the effectiveness of HRV biofeedback still need to be uncovered. This study aimed to disentangle the specific effects of HRV biofeedback from the effects of SPB realized alone. In total, 112 participants took part in the study. The parameters assessed were emotional (valence, arousal, and control) and perceived stress intensity as self-report variables and the root mean square of the successive differences (RMSSD) as a physiologic variable. A main effect of condition was found for emotional valence only, valence being more positive overall in the SPB-HRVB condition. A main effect of time was observed for all dependent variables. However, no main effects for the condition or time x condition interaction effects were observed. Results showed that for PRE and POST comparisons (referring, respectively, to before and after SPB), both SPB-HRVB and SPB-NoHRVB conditions resulted in a more negative emotional valence, lower emotional arousal, higher emotional control, and higher RMSSD. Future research might investigate psychophysiological differences between SPB-HRVB and SPB-NoHRVB across different time periods (e.g., long-term interventions), and in response to diverse psychophysiological stressors.

KEYWORDS

abdominal breathing, cardiac coherence, deep breathing, diaphragmatic breathing, heart rate variability, respiration, RMSSD

[Correction added on October 16, 2021 after first online publication: the term 'Psychophysiologic' has been changed to 'Psychophysiological' in article title.]

1 | INTRODUCTION

Heart rate variability (HRV) reflects the variation in the time interval between successive heartbeats (Berntson et al., 1997; Laborde et al., 2017; Malik, 1996). HRV biofeedback refers to providing an individual with a display of his/her live HRV signal, where slow-paced breathing (SPB)—the voluntary slowing down of breathing frequency (Russo et al., 2017)—is performed while visualizing heart rate, HRV, and/or sometimes the respiration signal (Lehrer & Gevirtz, 2014; Lehrer, Vaschillo, & Vaschillo, 2000; Shaffer & Meehan, 2020; Wheat & Larkin, 2010). In the past two decades, and particularly as a result of the seminal work of Lehrer, Vaschillo and colleagues (Lehrer et al., 2000, 2003; Lehrer & Vashillo, 2001; Vaschillo et al., 2002, 2006), the use of HRV biofeedback has become common in psychology, medicine, and other disciplines. Consequently, new interventions based on HRV biofeedback have been designed and shown to be successful as an adjunct treatment for psychological and medical conditions and to improve physical and executive performance (Lehrer, Kaur, et al., 2020).

As shown by several meta-analyses and systematic reviews, SPB coupled to HRV biofeedback interventions typically involving a series of sessions with a practitioner spread over a couple of weeks, and often completed with home practice, lead to improvements regarding stress and anxiety symptoms (Goessl et al., 2017), depressive symptoms (Pizzoli et al., 2021), fibromyalgia (Reneau, 2020), controlling substance craving (Alayan et al., 2018), enhancing executive functions (Tinello et al., 2021), and improving sports performance (Pagaduan, Chen, Fell, & Xuan Wu, 2020; Pagaduan, Chen, Fell, & Xuan Wu, 2021). However, despite the growing use of HRV biofeedback interventions, questions remain regarding the underlying mechanisms of this technique. In particular, the impact of displaying the heart rate signal as biofeedback while performing SPB has not yet been disentangled from the effects of SPB itself. The current study aimed to address this issue.

SPB, even used without biofeedback, has been found to be related to a range of positive outcomes, such as enhancing baroreflex sensitivity, decreasing symptoms of stress, anxiety, and depression, as well as enhancing cognitive performance (Bernardi et al., 1998, 2001, 2002; Gerritsen & Band, 2018; Hoffmann et al., 2019; Laborde, Allen, et al., 2021; Russo et al., 2017; Zaccaro et al., 2018). SPB influences respiratory sinus arrhythmia (RSA), a phenomenon in which heart rate is accelerated with inhalation and slowed down with exhalation (Berntson et al., 1993; Eckberg, 1983). Specifically, SPB increases RSA amplitude, the peak-to-trough heart rate difference in the breathing cycle (Cooke et al., 1998). In SPB, the inhalation and exhalation periods are controlled ("paced"), with exhalation being longer than inhalation—a pattern that provokes higher increases in the RSA (Bae et al., 2021; Laborde, Iskra, et al., 2021; Van Diest et al., 2014). SPB is usually realized at a pace of around six cycles per minute (cpm), while the spontaneous breathing frequency generally comprises between 12 and 20 cpm (Sherwood, 2006; Tortora & Derrickson, 2014). The frequency of 6 cpm is thought to trigger resonance effects, coupling the effects of RSA to the functioning of the baroreflex (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020).

Resonance is a built-in characteristic of the baroreflex system, which can be activated by various kinds of stimuli, such as SPB around 6 cpm. The cardiorespiratory system of each individual has a unique fixed resonance frequency, which produces the largest amplitude in blood pressure oscillations and the greatest heart rate oscillations by stimulating the baroreflex (Lehrer & Gevirtz, 2014; Lehrer et al., 2000; Shaffer & Meehan, 2020). Breathing at paced rates can stimulate the baroreflex, but it is expected to produce smaller resonance effects (Vaschillo et al., 2002). Despite some preliminary evidence (Lin et al., 2012; Steffen et al., 2017), a recent meta-analysis (Lehrer, Kaur, et al., 2020) did not find additional benefits of the resonance frequency breathing in comparison with a standard SPB frequency of 6 cpm (Lehrer, Kaur, et al., 2020). Consequently, the current study will use SPB at 6 cpm for all participants.

The mechanisms underlying the positive therapeutic effects of SPB regarding emotional, cognitive, and physical health are still debated. First, given that SPB stimulates the baroreflex, SPB might help to control blood pressure (Lehrer & Gevirtz, 2014; Lehrer, Kaur, et al., 2020; Shaffer & Meehan, 2020). Further, the in-phase relationship between the heart rate and breathing during SPB may help to improve gas exchange efficiency and consequently help in respiratory disease and other breathing disorders (Lehrer & Gevirtz, 2014; Lehrer, Kaur, et al., 2020). However, the heart rate and breathing are not always in phase during SPB (Lehrer et al., 2020), and consequently, further research is needed to confirm this hypothesis. Additionally, SPB might induce oscillatory activity in the brain, enhancing functional connectivity in brain networks involved in emotional regulation (Mather & Thayer, 2018). Overall, SPB is suggested to increase the activation of the vagus nerve (Gerritsen & Band, 2018)—the main nerve of the parasympathetic nervous system (Brodal, 2016)—which is suggested to underlie many of the positive therapeutic outcomes of SPB at the level of self-regulation, and in particular regarding emotion regulation, relaxation, cognition, and well-being (Gerritsen & Band, 2018). The manner in which SPB influences the vagus nerve is hypothesized to be through stimulation of baroreceptors and pulmonary afferent receptors that project to the brainstem at the level of the medulla via vagus nerve afferents, and innervate the parasympathetic relay nucleus, the nucleus of the solitary tract (Noble & Hochman, 2019). The NTS further regulates the cardiac vagal neurons of the nucleus ambiguous (Neff et al., 1998), which in turn regulate cardiac vagal activity (CVA), reflecting the activity of vagus nerve efferents regulating cardiac functioning (for a more detailed description of these pathways, see Noble & Hochman, 2019, Figure 2, p. 5).

CVA can be measured noninvasively using HRV (Berntson et al., 1997; Laborde, Mosley, et al., 2017; Malik, 1996). CVA, also referred to as vagally mediated HRV, is considered a marker of self-regulation (Holzman & Bridgett, 2017; Laborde et al., 2018b; Smith et al., 2017; Thayer et al., 2009). According to the neurovisceral integration model (Smith et al., 2017; Thayer et al., 2009), based on the central autonomic network (Benarroch, 1993), similar brain structures are involved in the regulation of emotion, cognition, and cardiac functioning. The neurovisceral integration model further assumes that CVA, considered as the output of the central autonomic network, reflects the regulation of emotional, cognitive, and cardiac processes. Importantly, the relationship between the heart and the brain is suggested to be bidirectional (Smith et al., 2017; Thayer et al., 2009; Thayer & Lane, 2009). This bidirectional connection can be used as an active mechanism for some techniques aiming to provoke physiological changes, such as SPB, which would then in turn influence central processes via integration within the central autonomic network (Benarroch, 1997; Clamor et al., 2016; Mather & Thayer, 2018). The action of SPB is thought to take place via the action on vagus nerve afferents described above, and ultimately reflected in the activity of vagus nerve efferents, that is, CVA (Benarroch, 1997; Noble & Hochman, 2019; Shaffer & Meehan, 2020; Thayer et al., 2009).

Several HRV parameters are thought to index CVA (Berntson et al., 1997; Laborde, Mosley, et al., 2017; Malik, 1996). In the time domain, these parameters include the root mean square of successive differences (RMSSD) and RSA, operationalized as the difference between the maximum and minimum cardiac interbeat interval per breath. In the frequency domain, the parameter reflecting CVA depends on the breathing frequency: when the breathing frequency comprises between 9 and 24 cpm, CVA is reflected in the high-frequency band, whereas in the case of a breathing frequency below 9 cpm, CVA is shifted to the low-frequency band (Kromenacker et al., 2018). SPB has been linked to CVA increases during both single sessions (e.g., You, Laborde, Salvotti, et al., 2021) and after long-term interventions (e.g., Laborde et al., 2019).

Biofeedback used in conjunction with SPB usually displays heart rate, HRV parameters (in particular those reflecting CVA), and sometimes the respiration signal (Lehrer & Gevirtz, 2014; Lehrer et al., 2000; Shaffer & Meehan, 2020). The rationale for using HRV biofeedback is based on various individuals or joint goals (Lehrer & Gevirtz, 2014; Lehrer et al., 2000; Shaffer & Meehan, 2020): (1) using HRV biofeedback as part of the protocol to determine the resonance frequency (for a detailed overview of how the resonance frequency is determined, see Shaffer & Meehan, 2020), (2) using HRV biofeedback combined with the respiratory signal during SPB training, to teach individuals to increase RSA by creating sinusoidal phase synchronous patterns of heart rate and respiration (Lehrer & Gevirtz, 2014), or (3) using HRV biofeedback during SPB to monitor training effectiveness, enabling potential adjustment of breathing pattern based on the visualization of the typical sinewave oscillations produced by SPB and act as positive reinforcement due to operant conditioning (Frank et al., 2010). The current study focuses on the latter aspect, given we adopt a standard SPB frequency at 6 cpm. As biofeedback, our participants will be provided with the heart rate signal, and in case irregular sinewaves are observed, they will be instructed to adjust their breathing pattern (e.g., following precisely the timing for inhalation and exhalation, breathing with continuous and constant airflow) until regular sinewaves of similar amplitude are observed.

A few studies have investigated the effects of combining SPB with biofeedback on CVA, during a single session (Wells et al., 2012), and in a long-term intervention (Chen, Sun, Wang, Lin, & Wang, 2016; Lin et al., 2012). In Wells et al. (2012), in which trained musicians were investigated, the effects of a 30-min SPB session with biofeedback were compared with a SPB session without biofeedback of similar duration and a control condition. Right after the SPB intervention, the two groups (with and without biofeedback) showed similar improvements in terms of CVA during a task involving the anticipation of an anxiety-producing task. Two other studies compared the effects of a long-term SPB intervention with and without biofeedback, consisting of 10 sessions (Lin et al., 2012) and 15 sessions (Chen et al., 2016). Although both studies concluded that the SPB intervention with biofeedback provided better effects on HRV, several issues confounded the interpretation regarding the role of HRV biofeedback. Specifically, in those studies, biofeedback was used to achieve several goals (determination of resonance frequency, training at the resonance frequency, using HRV biofeedback to increase RSA during training sessions), and different kinds of biofeedback were provided (heart rate, respiration, HRV frequency analysis). In other words, the study designs do not provide a clear understanding of the effects of biofeedback used as a monitoring tool. In addition, no clear HRV parameters reflecting CVA were included (i.e., SDNN, Total Power, HF nu, and LF/HF were considered). Consequently, given that only one study (Wells et al., 2012) investigated the addition of biofeedback during a single session SPB experiment using a between-subjects design and a modest sample size ($n = 44$), the current study aims to build on those findings using a within-subjects design, in order to account for the large interindividual differences in HRV (Quintana & Heathers, 2014). We should, however, note that our study involves HRV measurement during the SPB intervention and right after the intervention, but does not involve a stress task, contrary to Wells et al. (2012). Additionally, the current study focuses on a clearer CVA marker, RMSSD, using biofeedback specifically for monitoring SPB effectiveness. Given RMSSD has been shown to return to baseline immediately after a 15-min SPB task (You, Laborde, Salvotti, et al., 2021), the risks of carryover due to the within-subject design are estimated to be low. Finally, we endeavor to account for the potential learning effect by recruiting a large sample size.

The effects of SPB with and without biofeedback on effective self-report variables have only been investigated in one study (Wells et al., 2012). In trained musicians, a similar decrease in self-reported anxiety was found in both conditions. Furthermore, only a few studies examined the effects of a single SPB session without biofeedback on self-report affective variables (Gholamrezaei et al., 2021; Steffen et al., 2017; Szulczewski & Rynkiewicz, 2018; Van Diest et al., 2014; Wells et al., 2012; You, Laborde, Zammit, et al., 2021). Overall, the studies suggest a modulation of self-report affective variables by SPB. However, findings are mixed, and consequently the influence of SPB with or without biofeedback on self-reported affective parameters remains to be clarified. Interestingly, previous research has shown that increasing effectiveness expectations of SPB leads to improved affective experiences (Szabo & Kocsis, 2017). Additionally, biofeedback might increase expectations of success, due to the direct visualization of the expected physiological outcome acting as positive reinforcement (Frank et al., 2010). Besides triggering a learning process by prompting the adjustment of the breathing pattern if required and visualizing the direct result, biofeedback can also trigger cognitive-attributional changes by improving self-efficacy (Limmer et al., 2021). Self-efficacy is defined as people's beliefs in their capabilities (Bandura, 2010), and it is suggested to be a key mechanism in biofeedback (Fox et al., 2021; Nestoriuc & Martin, 2007). Based on these mechanisms, we would expect that displaying the heart rate signal to the participants and instructing them how to alter it can trigger a more positive affective experience.

In short, the psychophysiological effects of adding HRV biofeedback to SPB are still unclear. The current study aimed to address this issue by investigating the influence of SPB with (SPB-HRVB) and without (SPB-NoHRVB) HRV biofeedback (i.e., heart rate signal) on psychophysiological markers, namely CVA and the affective markers of emotional valence, emotional arousal, emotional control, and perceived stress intensity. Based on previous research, we hypothesized that (1) no differences will be found between the two groups regarding CVA during or after the SPB intervention (based on Wells et al., 2012); but (2) that the SPB-HRVB condition will trigger additional subjective affective benefits, given the positive reinforcement (Frank et al., 2010), self-efficacy enhancement (Fox et al., 2021; Nestoriuc & Martin, 2007), and potential reinforcing expectancy effects (Szabo & Kocsis, 2017) of HRV biofeedback. Specifically, in comparison with SPB-NoHRVB, we expect the SPB-HRVB condition to induce more positive emotional valence, lower emotional arousal, higher emotional control, and lower perceived stress.

2 | METHOD

2.1 | Participants

The determination of the sample size was based on previous research showing no differences in CVA between SPB realized with and without biofeedback, in a between-subject design with a total of 44 participants (Wells et al., 2012). Therefore, our calculation of the sample size aimed to be able to detect a small effect size ($f = 0.1$). A G*Power (Faul et al., 2009) a priori power calculation for repeated-measures ANOVA to detect a small effect size $f = 0.1$, power $(1-\beta) = 0.80$, correlation among repeated measures = 0.50, provided an estimated sample size of 109. In order to anticipate for potential dropouts and technical issues, a sample size of $N = 120$ was recruited, with 112 participants included in the final analysis (52 male, 60 female; $M_{\text{age}} = 21.6$ years, range = 18–31 years; BMI: $M = 23.3$, $SD = 2.3$; waist-to-hips ratio: $M = 0.81$, $SD = 0.08$). Exclusion criteria were any kind of self-reported cardiovascular, respiratory, or neurologic diseases, any psychiatric disorders, and regular medication potentially affecting the cardiovascular or respiratory systems, smoking, and the regular practice of breathing exercises including yoga.

2.2 | Material and measures

2.2.1 | Cardiac vagal activity indexed via heart rate variability

CVA was indexed via RMSSD, calculated from HRV. HRV was measured via an electrocardiography (ECG) device (Faros 180°, Bittium, Kuopio, Finland), at a sampling rate of 500 Hz. We used two disposable ECG pregelled electrodes (Ambu L-00-S/25, Ambu GmbH, Bad Nauheim, Germany). The negative electrode was placed on the right infraclavicular fossa (just below the right clavicle), whereas the positive electrode was placed on the left side of the chest, below the pectoral muscle in the left anterior axillary line. The Kubios software (University of Eastern Finland, Kuopio, Finland) was used to extract RMSSD and the other HRV parameters. The ECG signal was visually inspected for artifacts and corrected manually if needed (<0.001% of the total heartbeats) (Laborde, Mosley, et al., 2017). In order to provide an overview of the different HRV parameters, following Laborde, Mosley, et al. (2017), we also extracted heart rate and the standard deviation of the NN interval (SDNN) for the time domain and the frequency domain (fast Fourier transform), low frequency (LF: 0.04–0.15 Hz), high frequency (HF: 0.15–0.40 Hz), and the LF/HF ratio. Finally, we also extracted the respiratory frequency from the ECG signal, based on the ECG-derived respiration algorithm of Kubios (Tarvainen et al., 2014).

2.2.2 | Slow-paced breathing with and without biofeedback

A 5-min video showing a ball moving up and down at the rate of 6 cpm, based on the EZ-Air software (Thought Technology Ltd., Montreal, Canada), served as a breathing pacer. The video was displayed on a 15′ laptop screen. This stimulus has been used in previous research (e.g., Laborde et al., 2017; You, Laborde, Salvotti, et al., 2021). Participants were instructed to inhale continuously through the nose while the ball was going up and exhale continuously with pursed lips (Spahija & Grassino, 1996) when the ball was going down. The slow-paced breathing video was the same in both conditions (i.e., SPB-HRVB and SPB-NoHRVB). The only difference was that in the biofeedback condition, participants could visualize their heart rate signal using a smartphone (iPhone 5 SE, Apple, Cupertino, USA) via the smartphone app Elite HRV (https://elitehrv.com/; i.e., a graphical depiction of the heart rate values over time enabling to see the typical sinusoidal oscillations observed during SPB) while being connected via Bluetooth to a Polar H7 chest strap (Polar, Kempele, Finland). The Polar H7 chest strap has been found to provide a reliable estimate of the heart rate and HRV in comparison with the ECG gold standard (Plews et al., 2017). This enabled participants to see the classical oscillations in heart rate, with biofeedback illustrating the effects of SPB on RSA (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020). The correct realization of SPB was monitored by the experimenter during familiarization and during the main experiment. The experimenter first visually ensured that participants were breathing at 6 cpm while running the experiment. The breathing frequency was also checked post-hoc with the ECG-derived respiration algorithm of Kubios (Tarvainen et al., 2014).

2.2.3 | Visual analog scale—Perceived stress

A visual analog scale (VAS), consisting of a 100 mm vertical line, was used to assess perceived stress intensity. The instruction was “Please indicate on the line below how stressed you feel right now.” The line was anchored by the words “not stressed at all” at the extreme left of the line and “extremely stressed” at the extreme right of the line. Participants were required to cross a point somewhere on the line, corresponding to their subjective stress intensity. The value of perceived stress intensity was represented by the value (in cm) from the extreme left of the line. Previous research has used this scale to assess perceived stress intensity (Laborde et al., 2015; Lesage & Berjot, 2011; Lesage et al., 2012).

2.2.4 | Self-assessment manikin—Perceived emotional arousal, perceived emotional valence, and perceived control

The self-assessment manikin (Bradley & Lang, 1994) assesses the emotional state of an individual along three dimensions: valence, arousal, and control. The self-assessment manikin is a picture-oriented instrument containing five images for each of the three affective dimensions that the participant rates on a 9-point scale (1–9). The main instruction for the three dimensions was: “Please make a cross corresponding to how you feel right now.” Valence is depicted on a negative (a frowning figure), neutral, and positive figure (a smiling figure). The scale was anchored with the words “unpleasant” and “pleasant.” Higher scores reflect a more positive valence. Arousal is depicted ranging from low arousal (eyes closed) to high arousal (eyes wide open). The scale was anchored with the words “calm” and “activated.” Higher scores consequently represent higher arousal. Finally, dominance/control ranges from feeling controlled or submissive (a very small figure) to feeling in control or dominant (a very large figure). The scale was anchored with the words “controlled” and “in control.” Higher scores represent higher emotional control.

2.3 | Procedure

The study protocol was approved by a university research ethics committee (No. 037/2018). Participants were recruited via flyers at a local university campus and via posts on social network groups linked to the university. In line with recommendations for psychophysiological experiments involving HRV measurements (Laborde, Mosley, et al., 2017), participants were instructed to follow their usual sleep routine the night before the experiment, not to consume alcohol or engage in strenuous physical activity in the previous 24 hr, nor to drink or eat 2 hr before taking part in the experiment. All participants gave written informed consent before participating, and were informed that they could withdraw from the study at any time without explanation, and without any consequences. The participants attended the lab once, in accordance with the within-subject design. The whole session lasted 1hr. The full protocol is depicted in Figure 1. After being welcomed to the lab, they were asked to fill out an informed consent form and a demographic questionnaire (Fatisson et al., 2016; Laborde et al., 2018a; Laborde, Mosley, et al., 2017).

Participants were seated on a chair during the entire experiment, with the upper body and the arms being supported. The ECG Faros 180° device for HRV measurement and the Polar H7 chest strap to display the live heart rate signal was attached, and participants were familiarized with SPB using a video, training them to progressively decrease their breathing to 10 cpm, 8 cpm, and then 6 cpm during 2-min sequences. They were also able to see the heart rate biofeedback signal on Elite HRV during the familiarization, in order to enhance their understanding of its meaning during the experiment, particularly the typical sinusoidal oscillations observed with paced breathing (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020). Participants were made aware of the fact that heart rate tends to go up with inhalation and go down with exhalation. Participants were asked to pay attention to the regularity of the amplitude of the sinusoidal oscillations in the heart rate signal, to ensure that they were not deviating from the breathing pattern they had to follow. If deviations in the regularity of the amplitude of the sine-waves were observed, participants were then taught to adjust their breathing pattern, specifically regarding following precisely the inhalation and exhalation times. They were also reminded to breathe with continuous and constant airflow and breathing depth (i.e., shallowly) for the full duration of each phase (i.e., inhalation and exhalation). Observing the sinusoidal oscillations of regular amplitude in the heart rate signal consequently served as a positive reinforcement for the participants, helping them to know that they were performing the SPB task correctly. A detailed description of the participants' information can be found in Supporting Information 1. The familiarization video and the subsequent SPB stimuli were displayed on a 15′ laptop, and the smartphone displaying biofeedback was leaned (landscape position) against the laptop screen, to allow the participant to see both the SPB stimulus and the heart rate biofeedback signal at the same time.

Following the 3Rs of HRV, we implemented a resting–reactivity–recovery design (Laborde et al., 2018b; Laborde, Mosley, et al., 2017). The reactivity period corresponded to either SPB with or without biofeedback, whereas during the resting and recovery periods, participants were instructed to breathe spontaneously. All measurements were collected with eyes opened, knees at 90°, hands-on thighs, and lasted 5 min, following HRV recommendations (Laborde, Mosley, et al., 2017; Malik, 1996). At the end of each 5-min period, participants had to fill out the self-report measures (SAM and VAS). The order of the conditions with and without biofeedback was counterbalanced. A 5-min washout period took place between the two conditions, where the participants were prompted to breathe spontaneously. At the end of the experiment, the ECG device and the Polar H7 chest strap were detached, and participants were thanked and debriefed.

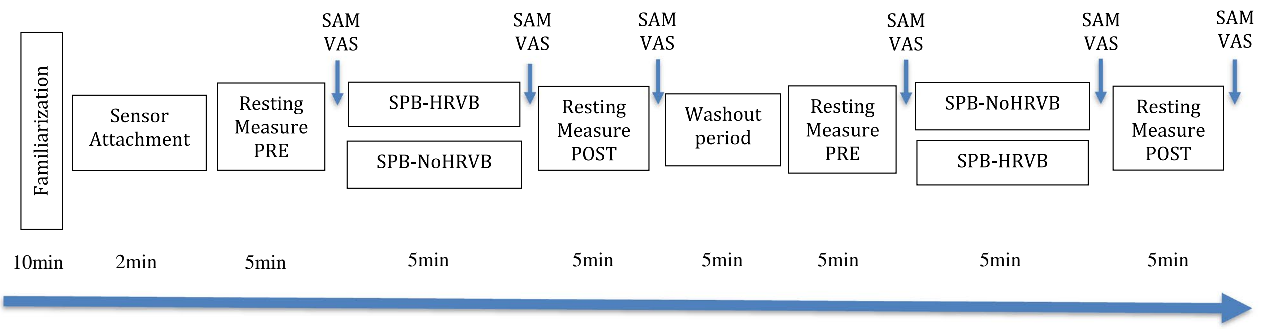

FIGURE 1 Experimental protocol. *Notes:* SAM: Self-Assessment Manikin; VAS: Visual Analogue Scale; HRVB: HRV Biofeedback

2.4 | Data analysis

The statistical analyses were computed using JASP (JASP Team, 2020). The ECG signal was imported into Kubios, and HRV variables were exported from the Kubios output. Data were checked for normality and outliers. Regarding outliers, 0.012% of the cases were found to be univariate outliers (>2 *SD*, *z*-scores higher than 2.58; none were >3.0 *SD*, with *z*-scores higher than 3.29). Running the analyses with outliers removed did not change the pattern of results and we report findings with potential outliers included in analyses. As the RMSSD data were nonnormally distributed, a log-transformation was applied, as is often recommended for HRV research (Laborde, Mosley, et al., 2017). The self-report variables were also mostly nonnormally distributed, and similar to RMSSD, we applied a log-transformation. We conducted a series of repeated measures ANOVA with Greenhouse–Geisser correction, with condition (SPB-HRVB vs. SPB-NoHRVB) and time (PRE, DURING, POST; referring to, respectively, resting, reactivity, and recovery) set as independent variables, with emotional valence, emotional arousal, emotional control, and perceived stress intensity as self-report-dependent variables (log-transformed), and log RMSSD as HRV-dependent variable indexing CVA.

3 | RESULTS

Descriptive statistics can be found in Table 1. Regarding log RMSSD, a significant main effect of time was found, $F(1.13, 125.08) = 398.18$, $p < .001$, partial $\eta^2 = 0.78$; no main effect of condition, $F(1, 111) = 1.47$, $p = .228$, partial $\eta^2 = 0.01$; and no interaction effect between time and condition, $F(1.89, 210.09) = 0.07$, $p = .937$, partial $\eta^2 = 0.00$. Regarding the main effect of time, post-hoc *t* tests were conducted applying a Bonferroni correction with alpha adjusted to $p = .017$ (0.05/3). Log RMSSD was found to be significantly higher DURING compared with PRE, $t(111) = 20.39$, $p < .001$, $d = 1.97$, and POST, $t(111) = 20.34$, $p < .001$, $d = 1.92$. No significant difference was found between PRE and POST, $t(111) = 2.362$, $p = .20$, $d = 0.22$.

Regarding emotional valence, a significant main effect of time was found, $F(1.94, 215.18) = 7.77$, $p < .001$, partial $\eta^2 = 0.07$; a significant main effect of condition, $F(1, 111) = 6.433$, $p = .013$, partial $\eta^2 = 0.06$; and no interaction effect between time and condition, $F(1.87, 207.76) = 0.84$, $p = .425$, partial $\eta^2 = 0.01$. Regarding the main effect of time, post-hoc *t* tests were conducted applying a Bonferroni correction with alpha adjusted to $p = .017$ (0.05/3). Emotional valence was found to be significantly lower DURING in comparison to PRE, with $t(111) = 3.90$, $p < .001$, $d = 0.37$, and in comparison to POST, with $t(111) = 3.20$, $p = .005$, $d = 0.30$. No significant differences were found between PRE and POST, with $t(111) = 0.29$, $p = 1.000$, $d = 0.03$. Regarding the main effect of condition, emotional valence was found to be higher in SPB-HRVB than in SPB-NoHRV, with $t(111) = 2.53$, $p = .001$, $d = 0.25$.

Regarding emotional arousal, a significant main effect of time was found, $F(1.94, 216.29) = 31.83$, $p < .001$, partial $\eta^2 = 0.22$; no main effect of condition, $F(1, 111) = 3.80$, $p = .054$, partial $\eta^2 = 0.03$; and no interaction effect between time and condition, $F(1.99, 221.63) = 0.75$, $p = .473$, partial $\eta^2 = 0.01$. Regarding the main effect of time, further post-hoc *t* tests were conducted, applying a Bonferroni correction with alpha adjusted to $p = .017$ (0.05/3). Emotional arousal was found to be significantly lower DURING compared with PRE, $t(111) = 8.07$, $p < .001$, $d = 0.77$, and POST, $t(111) = 6.05$, $p < .001$, $d = 0.57$. No significant difference was found between PRE and POST, $t(111) = 1.53$, $p = .382$, $d = 0.15$.

Regarding emotional control, a significant main effect of time was found, $F(1.94, 214.79) = 19.55$, $p < .001$, partial $\eta^2 = 0.15$; no main effect of condition, $F(1, 111) = 1.920$, $p = .017$, partial $\eta^2 = 0.02$; and no interaction effect between time and condition, $F(1.93, 213.77) = 2.55$, $p = .083$, partial $\eta^2 = 0.02$. Regarding the main effect of time, post-hoc *t*-tests were conducted applying a Bonferroni correction with alpha adjusted to $p = .017$ (0.05/3). Emotional control was found to be significantly higher DURING compared with PRE, $t(111) = 4.80$, $p < .001$, $d = 0.45$, and POST, $t(111) = 6.30$, $p < .001$, $d = 0.60$. No significant difference was found between PRE and POST, $t(111) = 0.62$, $p = 1.000$, $d = 0.06$.

Regarding perceived stress intensity, a significant main effect of time was found, $F(1.73, 192.11) = 8.09$, $p < .001$, partial $\eta^2 = 0.07$; no main effect of condition, $F(1, 111) = 2.18$, $p = .142$, partial $\eta^2 = 0.02$; and no interaction effect between time and condition, $F(1.70, 188.87) = 1.38$, $p = .253$, partial $\eta^2 = 0.01$. Regarding the main effect of time, post-hoc *t* tests were conducted applying a Bonferroni correction with alpha adjusted to $p = .017$ (0.05/3). Perceived stress intensity was found to be significantly lower DURING compared with PRE, $t(111) = 4.91$, $p < .001$, $d = 0.46$, significantly higher PRE in comparison with POST, $t(111) = 2.63$, $p = .029$, $d = 0.25$, but not different between DURING and POST, $t(111) = 1.11$, $p = .814$, $d = 0.10$.

4 | DISCUSSION

The aim of this study was to distinguish the effects of SPB with HRV biofeedback (i.e., displaying the heart rate signal), from the effects of performing SPB alone on

TABLE 1 Descriptive statistics

	SPB with biofeedback			SPB without biofeedback		
	PRE	DURING	POST	PRE	DURING	POST
SAM—Emotional valence	6.19 ± 1.17	5.80 ± 1.14	6.35 ± 1.29	6.18 ± 1.43	5.60 ± 1.29	6.07 ± 1.72
SAM—Emotional valence (log)	0.79 ± 0.08	0.76 ± 0.09	0.80 ± 0.09	0.78 ± 0.11	0.74 ± 0.10	0.76 ± 0.14
SAM—Emotional arousal	3.54 ± 1.72	2.52 ± 1.33	3.13 ± 1.08	3.39 ± 1.55	2.16 ± 1.10	3.16 ± 1.75
SAM—Emotional arousal (log)	0.48 ± 0.26	0.34 ± 0.24	0.47 ± 0.17	0.48 ± 0.23	0.28 ± 0.22	0.42 ± 0.28
SAM—Emotional control	4.89 ± 1.21	6.02 ± 1.41	4.82 ± 1.11	4.99 ± 1.43	5.63 ± 1.92	4.90 ± 1.65
SAM—Emotional control (log)	0.67 ± 0.15	0.77 ± 0.11	0.67 ± 0.10	0.68 ± 0.13	0.72 ± 0.18	0.66 ± 0.18
VAS—Perceived stress intensity	6.71 ± 1.75	5.72 ± 2.27	6.23 ± 2.22	6.48 ± 1.56	6.09 ± 1.83	6.43 ± 2.26
VAS—Perceived stress intensity (log)	0.81 ± 0.13	0.71 ± 0.23	0.75 ± 0.27	0.80 ± 0.12	0.76 ± 0.15	0.77 ± 0.21
Mean RR (ms)	872.64 ± 115.53	912.00 ± 107.73	880.35 ± 115.63	874.08 ± 119.54	915.33 ± 112.26	882.03 ± 118.58
SDNN (ms)	54.76 ± 22.84	125.93 ± 31.34	57.79 ± 24.34	53.82 ± 21.31	124.14 ± 30.26	55.81 ± 21.05
Mean HR (bpm)	69.93 ± 9.08	66.67 ± 7.61	69.30 ± 8.89	69.86 ± 9.09	66.49 ± 7.86	69.19 ± 8.91
RMSSD (ms)	47.23 ± 21.02	90.94 ± 33.83	48.34 ± 22.18	46.08 ± 20.26	89.83 ± 32.61	46.94 ± 19.55
RMSSD (log)	1.63 ± 0.20	1.93 ± 0.17	1.64 ± 0.20	1.62 ± 0.19	1.92 ± 0.17	1.63 ± 0.19
LF (ms^2)	2,264.46 ± 2,988.34	14,802.69 ± 6,968.72	2,545.98 ± 3,066.08	2,149.27 ± 2,512.91	14,572.80 ± 6,897.28	2,309.41 ± 2,415.58
HF (ms^2)	907.75 ± 837.13	1,939.94 ± 1,795.83	917.31 ± 903.62	864.25 ± 834.28	1,823.40 ± 1,528.21	892.66 ± 789.42
LF/HF	2.97 ± 2.38	12.49 ± 8.82	3.67 ± 3.20	3.56 ± 3.76	11.95 ± 7.22	3.61 ± 3.57
Respiratory frequency (cpm)	16.91 ± 3.20	6.45 ± 0.30	16.23 ± 3.58	16.83 ± 3.30	6.45 ± 0.28	16.05 ± 3.35

Abbreviations: bpm, beats per minute; cpm, cycles per minute; HF, high frequency; HR, heart rate; LF, low frequency; RMSSD, root mean square of the successive differences; RR, time interval between two successive R peaks in the electrocardiogram; SAM, self-assessment manikin; SDNN, standard deviation of all RR intervals; SPB, slow-paced breathing; VAS, visual analog scale.

psychophysiological parameters. Our first hypothesis regarding CVA was supported with no differences found between SPB-HRVB and SPB-NoHRVB during and after SPB. However, our second hypothesis was mostly not supported with no differences emerging between the effects of SPB-HRVB and SPB-NoHRVB on arousal, and control, or perceived stress intensity, with the exception of emotional valence being more positive in the SPB-HRVB condition.

Regarding the first hypothesis, results showed a similar increase in CVA from PRE to DURING, and a decrease in CVA from DURING to POST, in both SPB-HRVB and SPB-NoHRVB conditions. Regarding the effect of HRV biofeedback, our findings are in line with the only previous study (Wells et al., 2012) comparing SPB-HRVB and SPB-NoHRVB exploring short-term duration (30 min), where no differences were found in CVA parameters between these conditions. However, we have to note that our results are not directly comparable with those of Wells et al. (2012), given we measured CVA during the SPB intervention and right after at rest, whereas Wells et al. (2012) measured it after the SPB intervention while participants were engaged in an anxiety-provoking task. Our finding indicates that the physiological effects of SPB—which are linked to the activation of the vagus nerve (Gerritsen & Band, 2018; Zaccaro et al., 2018) potentially via the stimulation of the baroreflex (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020), the action on pulmonary afferents (Noble & Hochman, 2019), and the creation of brain oscillations (Mather & Thayer, 2018)—are not influenced by the presentation of the heart rate signal as biofeedback. The absence of difference in CVA between both conditions may suggest that the participants adjusted adequately their breathing pattern during SPB-NoHRVB even without visualizing the heart rate biofeedback signal. The increase of CVA observed with SPB and its subsequent decrease after completing the SPB task is in line with previous research (e.g., Hoffmann et al., 2019; Laborde, Iskra, et al., 2021; You, Laborde, Salvotti, et al., 2021), illustrating that the short-term effects of SPB on CVA are similar to the action of a "switch-on/switch-off" power switch, with CVA returning to baseline immediately after SPB stops. Nonetheless, preliminary evidence indicates that chronic increases in resting CVA can also be achieved with a long-term SPB-NoHRVB intervention (15 min/day during 30 days) (Laborde et al., 2019). Given the positive benefits documented with long-term SPB-HRVB interventions at 6 cpm (Lehrer, Kaur, et al., 2020), future research should investigate further if similar benefits can also be achieved with SPB-NoHRVB, given the absence of costs and technology related to this technique.

Regarding the effective self-report variables, the only difference found between SPB-HRVB and SPB-NoHRVB was related to emotional valence, more positive in SPB-HRVB. These results partially contrast with our hypothesis, due to our expectation that HRV biofeedback would also lead to a less arousing and less stressful experience of SPB, with increased emotional control. The more positive emotional valence in SPB-HRVB may be due to positive reinforcement (Frank et al., 2010), increased self-efficacy biofeedback (Fox et al., 2021; Nestoriuc & Martin, 2007), and increased effectiveness expectancy (Szabo & Kocsis, 2017). In comparison with PRE and POST, we saw similar significant patterns of results in both conditions (SPB-HRVB and SPB-NoHRVB), with a decrease in emotional arousal, a more negative emotional valence, and an increase in emotional control. These findings are generally in line with previous research (Gholamrezaei et al., 2021; Van Diest et al., 2014; Wells et al., 2012) illustrating the overall subjective ratings of relaxing effects of SPB and increased emotional control, suggesting that this technique might be an effective coping strategy. The decrease in emotional valence also reflects previous findings applying short-term SPB (Gholamrezaei et al., 2021; Szulczewski & Rynkiewicz, 2018; Van Diest et al., 2014; You, Laborde, Zammit, et al., 2021), although mixed evidence was found by Steffen et al. (2017) using the individual resonance frequency. The more negative emotional valence experienced while performing SPB (both for SPB-HRVB and SPB-NoHRVB) in comparison with PRE and POST resting measurements might reflect some breathing discomfort and a tendency to hyperventilate (Szulczewski & Rynkiewicz, 2018; Van Diest et al., 2014). In order to address breathing discomfort, it was suggested to provide participants with positive stimuli during SPB-NoHRVB (Allen & Friedman, 2012), which was thereafter found to have been experienced as more positive than SPB-HRVB. To address hyperventilation, providing antihyperventilation instructions may help (Szulczewski, 2019a). However, antihyperventilation instructions might not be sufficient (Szulczewski & Rynkiewicz, 2018), therefore SPB training could be an effective way to decrease hyperventilation (Szulczewski, 2019b).

Our study has some strengths, including the use of a within-subject design, a large sample size (sufficient to detect small effect sizes), and an investigation of the HRV biofeedback (i.e., visualizing the heart rate signal) effects on SPB realized at 6 cpm without the confounding factor of the individual resonance frequency. However, some important limitations also need to be considered when interpreting findings. (1) Our design did not include a control group not performing a breathing task, which limits the interpretation of the results linked to the psychophysiological variables assessed. (2) We focused on a single, short-term SPB session. The effects of HRV biofeedback on psychophysiological outcomes might differ when SPB is tested over a longer time frame (Chen et al., 2016; Lin et al., 2012). (3) Regarding the dependent variables of interest, future research may consider in addition to the HRV parameters reported here calculating RSA as the difference between the maximum and minimum cardiac interbeat interval per breath, similar to Van Diest et al. (2014). (4) We did not measure respiratory frequency with a specific device such as a respiratory belt but instead used the ECG-derived respiration algorithm of Kubios (Tarvainen et al., 2014). Even if this algorithm is deemed valid, it remains a calculation based on the ECG signal, and therefore, a more direct online measurement of respiratory frequency, also enabling accurate measurement of the inhalation and exhalation timing, as well as of the respiratory depth, should be considered in future research. Further, we did not measure respiratory parameters such as the partial pressure of end-tidal carbon dioxide ($PETCO_2$), which might help to detect hyperventilation. We also did not document systematically whether our participants experienced symptoms of hyperventilation. Based on these limitations, it is therefore unclear whether the conditions differed in terms of respiratory parameters. (5) We tested only healthy participants and it would be interesting to see whether the subjective effects of HRV biofeedback differ in clinical samples such as people with anxiety disorders (e.g., posttraumatic stress disorder). (6) Our participants were untrained to SPB. Training seems not only to decrease hyperventilation but also to make SPB more pleasant (Szulczewski, 2019b). In general, it seems that studies on untrained individuals provide limited knowledge about the emotional effects of SPB, given it may not be comfortable for novices. Future research may consequently clarify the amount of training necessary to achieve a positive emotional experience with SPB and to which extent the use of biofeedback may contribute to potentially accelerate this process. (7) We tested only one modality of SPB and future research could manipulate the characteristics of SPB, such as testing different inhalation/exhalation ratios (Bae et al., 2021; Laborde, Iskra, et al., 2021; Van Diest et al., 2014), and the presence of a respiratory pause between respiratory phases (Laborde, Iskra, et al., 2021; Russell et al., 2017). (8) Future research might also consider testing the effects of HRV biofeedback when negative emotions are elicited and initial arousal is not low, for example, in reaction to psychological or physical stressors, as suggested by Szulczewski and Rynkiewicz (2018). (9) Our experimental design could not fully address the placebo effect, given it is obvious that participants are receiving an intervention in both SPB-HRVB and SPB-NoHRVB conditions. Suggestion certainly plays a role in SPB, as in all pharmacological and nonpharmacological interventions (Petrie & Rief, 2019), and future research should attempt to clarify its role. (10) We tested only one modality of biofeedback here, the presentation of the heart rate signal to enable the potential correction of the breathing pattern based on the observation of the regularity of the sinewaves. However, given the breathing frequency was constrained at 6 cpm for each participant, they did not have the possibility to change their breathing frequency based on the biofeedback signal, which is the most traditional biofeedback approach based on SPB and HRV and which was found to provoke increases in CVA (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020; Vaschillo et al., 2006). An additional limitation of constraining the breathing frequency to 6 cpm is that for some people whose resonance frequency is further away from 6 cpm, such as 4.5 cpm (Vaschillo et al., 2002, 2006), they may have had fewer benefits regarding CVA, and also potentially regarding the perceived affective variables. That said, for most people, the resonance frequency is close to 6 cpm (Lehrer & Gevirtz, 2014; Shaffer & Meehan, 2020; Vaschillo et al., 2006). (11) Finally, our experimental protocol could have been more parsimonious, given that we used a combination of two devices, an ECG device to record the ECG signal and a chest strap to display the HRV biofeedback. During the familiarization phase, we made sure that participants were able to focus on both the breathing pacer and the heart rate signal. That said, we did not control to which extent our participants actually monitored their heart rate while performing SPB. Since the smartphone was leaning on the computer screen, it provided the participants with the closest experience of displaying the heart rate signal on the same computer screen. Using a specific software coupling the HRV biofeedback and the ECG measurement equipment (potentially measuring as well respiratory parameters) would require only one device. This would potentially contribute to an enhanced subjective experience of the participant. Our choice to use the smartphone app Elite HRV to display the HRV biofeedback was based on the rationale that it represents a low-cost option in comparison with more expensive biofeedback software and hence reflects the use of HRV biofeedback available to a larger audience.

5 | CONCLUSION

To conclude, this study showed that the positive psychophysiological effects of SPB with HRV biofeedback (i.e., displaying the heart rate signal) as a monitoring system did not differ from those without HRV biofeedback, with the exception of a more positive emotional valence for SPB-HRVB. Even if the role of HRV biofeedback compared with SPB alone needs to be investigated in different contexts, such as over a longer time period and in response to diverse psychophysiological stressors, these results can be seen as promising as they highlight the benefits achieved solely with SPB. Although further research needs to address the shortcomings of the study mentioned above, our findings suggest that SPB possesses some promising characteristics, based on its positive psychophysiological effects. In addition, it requires neither expensive equipment nor specific knowledge to be implemented and also appears to be a suitable low-cost, nonpharmacological relaxation technique. The small side effects documented, such as dyspnea and hyperventilation could be addressed by instructing individuals to breathe more shallowly (Szulczewski & Rynkiewicz, 2018), by providing them with SPB training (Szulczewski, 2019b), and by adapting the respiratory pacer with pleasant stimuli (Allen & Friedman, 2012).

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AUTHOR CONTRIBUTIONS

Sylvain Laborde: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Project administration; Resources; Writing-original draft. **Mark S. Allen:** Conceptualization; Funding acquisition; Investigation; Writing-original draft. **Uirassu Borges:** Conceptualization; Investigation; Writing-original draft. **Maša Iskra:** Investigation; Visualization; Writing-review & editing. **Nina Zammit:** Investigation; Validation; Writing-original draft. **Min You:** Conceptualization; Writing-original draft; Writing-review & editing. **Thomas Hosang:** Conceptualization; Writing-original draft. **Emma Mosley:** Conceptualization; Writing-original draft. **Fabrice Dosseville:** Conceptualization; Writing-original draft.

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.
Supplementary Material

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