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ORIGINAL ARTICLE

Squeeze the beat: Enhancing cardiac vagal activity during resonance breathing via coherent pelvic floor recruitment

Josef Martin Tatschl | **Andreas Richard Schwerdtfeger**

Department of Psychology, Health Psychology Unit, University of Graz, Graz, Austria

Correspondence
Josef Martin Tatschl, Health Psychology Unit, University of Graz, Graz, Austria.
Email: josef.tatschl@edu.uni-graz.at

Funding information
Karl-Franzens-Universit auml;t Graz

Abstract

Resonance breathing (RB) has been shown to benefit health and performance within clinical and non-clinical populations. This is attributed to its baroreflex stimulating effect and the concomitant increase in cardiac vagal activity (CVA). Hence, developing methods that strengthen the CVA boosting effect of RB could improve its clinical effectiveness. Therefore, we assessed whether supplementing RB with coherent pelvic floor activation (PRB), which has been shown to entrain the baroreflex, yields stronger CVA than standard RB. $N = 32$ participants performed 5-min of RB and PRB, which requires to recruit the pelvic floor during the complete inspiratory phase and release it at the initiation of the expiration. CVA was indexed via heart rate variability using RMSSD and LF-HRV. PRB induced significantly larger RMSSD ($d = 1.04$) and LF-HRV ($d = 0.75$, $ps < .001$) as compared to RB. Results indicate that PRB induced an additional boost in CVA relative to RB in healthy individuals. However, subsequent studies are warranted to evaluate whether these first findings can be replicated in individuals with compromised health, including a more comprehensive psychophysiological assessment to potentially elucidate the origin of the observed effects. Importantly, longitudinal studies need to address whether PRB translates to better treatment outcomes.

KEYWORDS

baroreflex, cardiac vagal activity, heart rate variability, pelvic floor, resonance breathing, slow-paced breathing

1 | INTRODUCTION

Breathing exercises have been shown to foster psychophysiological well-being and health via modulating the respiratory pattern including length, depth, and rhythmicity (Gerritsen & Band, 2018). Thus, respiratory training has been suggested as a promising tool that could improve public health due to its good safety profile as well as cost-efficacy (Lavretsky & Feldman, 2021). Within these techniques, slow-paced breathing at 0.1 Hz plays a pivotal role as it amplifies heart rate variability (HRV), which describes the variation in inter-beat intervals (Berntson et al., 1997; Vaschillo et al., 2006). Precisely, this type of breathing increases the respiratory sinus arrhythmia (RSA), which

[Correction added on September 10, 2022, after first online publication: Figure 1 has been modified.]

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describes the phenomenon of increasing heart rate (HR) during inhalation and deceleration during exhalation (Schwerdtfeger et al., 2020; Shaffer & Meehan, 2020). The main mechanism driving the RSA amplification during 0.1 Hz breathing is the baroreflex, which has an eigenfrequency of approximately 0.1 Hz and innervates the heart via an afferent-efferent feedback loop (Schwerdtfeger et al., 2020; Vaschillo et al., 2006). In brief, blood pressure oscillations activate baroreceptors (i.e., stretch receptors) in the aortic system, which send these signals to the brain stem and in turn, modulate cardiac vagal activity (CVA) to adapt the HR accordingly (Shaffer & Meehan, 2020). Consequently, adapting the respiratory rate to the intrinsic frequency of the baroreflex loop ultimately stimulates the latter, increasing the afferent input to the brain, eventually manifesting in increased CVA (e.g., Shaffer & Meehan, 2020). Therefore, this type of breathing has been labeled resonance breathing (RB) (Lehrer et al., 2003; Vaschillo et al., 2006). Additionally, abdominal breathing (an integral part of RB) has been suggested to contribute to this phenomenon via activating pulmonary stretch receptors, which in turn could aid in augmented cardiac vagal control as well (Noble & Hochman, 2019; Russo et al., 2017). Accordingly, when breathing at 0.1 Hz, HR oscillations occur predominantly within the low-frequency domain (LF-HRV = 0.04–0.15 Hz), which is mediated predominantly by vagal efferent control (Kromenacker et al., 2018; Shaffer & Ginsberg, 2017). In addition to amplified LF-HRV, RB increases the root mean square of successive differences (RMSSD), which reliably indexes CVA across different respiratory frequencies (Penttilä et al., 2001; Shaffer & Meehan, 2020). Noteworthy, under resting conditions the magnitude of acute RMSSD augmentation occurring during a RB session seems independent of its duration and returns to pre-session resting levels post-practice (You, Laborde, Salvotti, et al., 2021; You, Laborde, Zammit, et al., 2021). On the contrary, respiration seems to be sensitive to session length with longer RB intervals yielding lower post-session resting breathing rates, which in response could transfer to improved psychophysiological functioning (e.g., You, Laborde, Zammit, et al., 2021). Importantly, practicing RB regularly has been shown to improve psychological and physical health as well as performance, which at least partly is attributed to the CVA-enhancing effect of this distinct breathing pattern (Lehrer et al., 2020). Therefore, we set out to advance the current RB paradigm, targeting novel ways to amplify its described cardiac resonance effects, emphasizing CVA.

On a general note, the individual resonance frequency to maximize HRV ranges between 4.5 to 6.5 breaths per minute (BPM) averaging roughly 6 BPM (Vaschillo et al., 2002, 2006). Hence, HRV biofeedback can be used to optimize one's breathing pattern to facilitate RB (Lehrer et al., 2003, 2013). While preliminary research suggests stronger treatment effects for HRV biofeedback as compared to paced RB regarding blood pressure regulation, more research is needed to validate potential differences in effectiveness between the two RB modalities (Lin et al., 2012; Shaffer & Meehan, 2020). Noteworthy, a recent study by Laborde et al. (2022) showed no additional benefit on CVA when paced 0.1 Hz breathing (i.e., participants were instructed to strictly adhere to a respiratory rate of 6 BPM) was supplemented with visual feedback of the heart rate. While these findings support the value of simple paced breathing at a fixed frequency (i.e., 0.1 Hz) for CVA augmentation, they also suggest that adapting the respiratory pattern during HRV biofeedback seems crucial to optimally utilize the latter to maximize HRV. Of note, both biofeedback-guided RB as well as paced RB seems effective in improving psychological well-being and physical health as well as athletic performance (Lehrer et al., 2020). Noteworthy, RB seems to be especially effective in improving emotional well-being, providing a feasible behavioral intervention to treat depression and/or anxiety (Goessl et al., 2017; Tatschl et al., 2020).

It has been suggested that the RB-induced cardiac resonance transfers to strengthened functional connectivity within brain regions relevant to emotion regulation, via synchronizing and amplifying blood flow to the respective areas (Mather & Thayer, 2018). Of note, recent findings support this hypothesis as two independent studies showed increased functional connectivity between the prefrontal cortex and the amygdala after several weeks of biofeedback-guided RB (Nashiro et al., 2021; Schumann et al., 2021). Importantly, these effects seem to be driven by the repetitive amplification of HRV during RB rather than the contemplative effort, as a sham-control group showed no such effects (Nashiro et al., 2021). These findings point out that the health-promoting effects of RB should be driven by the magnitude of cardiac oscillations and CVA, respectively (Lehrer & Gevirtz, 2014; Schwerdtfeger et al., 2020; Shaffer & Meehan, 2020).

However, to date, only a few studies have aimed to advance the current RB paradigm targeting CVA. For example, modulating the inspiratory to expiratory ratio with longer exhalation as compared to inspiration seems to increase CVA during RB as well as during normal resting breathing rates (Bae et al., 2021; Laborde et al., 2021; Van Diest et al., 2014). Noteworthy, applying inspiratory threshold loading has been found to result in stronger cardiac resonance as compared to unloaded RB, which seems to be strengthened with increasing loads (Gholamrezaei et al., 2019, 2021a). On the contrary, inducing natural inspiratory resistance via unilateral nostril breathing or contracting the glottis muscles during inspiration seems to offer no incremental value regarding cardiac-hemodynamic stimulation (Gholamrezaei et al., 2021a;

Mason et al., 2013). Noteworthy, the current standard practice during RB, pursed lips breathing (i.e., nasal inhalation and exhalation via pursed lips) inducing a higher expiratory load than nasal exhalation, yielded significantly less CVA than a device-induced inspiratory load of 10 cm H_2O (Gholamrezaei et al., 2021a). [Correction added on October 10, 2022, after first online publication: mmHg has been updated to cm H_2O in the previous sentence]. Importantly, these add-on effects seem to be mediated by stronger baroreflex stimulation in response to augmented systolic blood pressure oscillations due to inspiratory loads likely amplifying intrathoracic pressure (Gholamrezaei et al., 2019, 2021a). Hence, these findings suggest that the CVA boosting effects of traditional RB could be amplified by utilizing additional techniques.

It is worth mentioning in this regard that non-respiratory stimuli like rhythmical muscle tension seem to exert cardiovascular resonance at 0.1 Hz as well (Lehrer et al., 2009; Shaffer et al., 2022; Vaschillo et al., 2011). Noteworthy, the moola bandha, a yoga technique describing the recruitment of the pelvic floor muscles has been suggested to stimulate the autonomic nervous system (Brotto et al., 2009). Of note, recent research has shown that voluntary pelvic floor recruitment could represent a feasible approach to induce cardiac resonance (Bastos et al., 2020). Precisely, during a pelvic floor muscle endurance test consisting of repetitive 5-second bouts of pelvic muscle activation, separated by 5-second pauses (i.e., 0.1 Hz), heart rate seemed to behave in coherence with the de−/activation cycle (Bastos et al., 2020). Although HRV was not assessed by Bastos et al. (2020), heart rate peaked during pelvic muscle contractions and decreased during the releasing phase (Bastos et al., 2020). As breathing was explicitly not in coherence with pelvic floor recruitment, the latter seems to have generated cardiac resonance similar to preceding studies using larger muscle groups (Bastos et al., 2020; Lehrer et al., 2009; Vaschillo et al., 2011). Of note, compared to breathing-generated resonance, rhythmical muscle tension seems to be accompanied by an increase in the sympathetic drive (e.g., Bastos et al., 2020; Lehrer et al., 2009; Vaschillo et al., 2011). However, pelvic floor recruitment might provide a unique stimulus to entrain the cardiovascular system beyond the general effects of muscle activation, especially when combined with RB. Precisely, the pelvic muscles and their intentional control, respectively, have recently been explored as a tool to optimize respiration, which we suggest could even enhance the resonance effects observed during 0.1 Hz breathing (Gordon & Reed, 2020). For example, by modulating intra-abdominal pressure in a functional manner, voluntary pelvic floor activation during the inspiratory phase could affect venous return, ultimately boosting baroreflex stimulation (Kitano et al., 1999; Russo et al., 2017; Takata et al., 1990; Takata & Robotham, 1992). Intriguingly, several weeks of pelvic floor training seem to improve systolic blood pressure in addition to increasing baroreflex sensitivity, emphasizing its potential to modulate the cardiovascular system (da Silva Corrêa et al., 2020). Taken together, these findings suggest that the prototypic increase in HR oscillations observed during RB might be augmented by utilizing pelvic floor recruitment as a coherent complementary stimulus.

Therefore, building on the above-mentioned evidence, this study aimed at evaluating whether RB yields stronger cardiac resonance, emphasizing CVA when supplemented with coherent de−/activation of the pelvic floor. Precisely, we hypothesized that recruiting the pelvic floor muscles during inspiration and releasing it during the expiratory phase, yields larger CVA than standard RB without pelvic floor de−/activation. Thus, we expected higher RMSSD and LF-HRV during pelvic floor assisted RB (PRB) as compared to standard RB (RB).

2 | METHOD

In absence of previous studies using PRB, the sample size was built on the smallest effect of interest, which was set at a medium-sized effect of Cohen's f of 0.25. This is in line with prior research citing the medium-sized effects of complementary stimuli on CVA during 0.1 Hz breathing (Gholamrezaei et al., 2019, 2021a). At an alpha level of .05 and a power (1 − beta) of .80, a target sample size of $N = 28$ was retrieved (G*Power; Faul et al., 2007). Exclusion criteria were self-reported habitual and/or acute intake of medication that may modulate respiration and/or heart dynamics and/or any acute or chronic diseases that could influence HRV, like cardiovascular diseases or neurological diseases, including dysfunction of the pelvic floor as well as pregnancy or child delivery within 12 months prior to study participation (Elenskaia et al., 2011). Additionally, participants who reported regularly to engage in pelvic floor training and/or breathing exercises were excluded. The final sample consisted of 32 participants (47% female; $\text{Age}_{\text{years}}$: M = 28.63, SD = 8.84, Range = 19–62; BMI: M = 23.40, SD = 3.55, Range = 18.93–33.08). The study was approved by the Ethics Committee of the University of Graz (GZ. 39/13/63 ex 2020/21).

2.1 | Materials and measures

R-R intervals (RRI) were assessed by means of the POLAR H10 chest strap (Polar Electro, Finland) with a RRI resolution rate of 1 ms, recorded with the HRV Logger App (HRV Logger, Marco Altini). The Polar H10 derives RRIs from an inbuilt ECG processor and has been validated against a 3-lead ECG Holter, exhibiting equal precision during rest and more accurate RRI detection during exercise, thus suggesting valid RRI assessment (Gilgen-Ammann et al., 2019).

RRIs were imported to KUBIOS Premium (V. 3.5.0) to analyze HRV (Tarvainen et al., 2014). The RRI time series was visually inspected and the inbuilt KUBIOS filter (automatic correction) was applied when necessary (Lipponen & Tarvainen, 2019). RMSSD and LF-HRV (Fast Fourier transform) as reliable indicators of CVA during slow-paced breathing were assessed (Kromenacker et al., 2018; Laborde et al., 2017; Shaffer & Meehan, 2020). While RMSSD provides a global measure of CVA, LF-HRV emphasizes the baroreflex-related HR oscillations, expressing the unique respiration-driven stimulation of the cardiovascular system during RB (Shaffer & Meehan, 2020).

2.2 | Manipulation checks

2.2.1 | Respiration

Participants were monitored by the investigator during the experiment via two cameras, providing a frontal (i.e., ≈0°) as well as a side view (i.e., ≈90°), respectively, allowing to visually control whether participants executed the instructed breathing pace via observing bodily movements. Successful 0.1 Hz breathing also results in HR oscillations predominantly within the LF-band, peaking at the respective respiratory rate (i.e., ≈0.1 Hz; Shaffer & Meehan, 2020). Additionally, the respiratory rate was obtained from the KUBIOS RRI-derived respiration algorithm, which however seems to overestimate breathing rates when respiration approaches 0.1 Hz by approximately 0.0493 Hz (i.e., three breaths per minute; Lipponen & Tarvainen, 2021).

2.3 | Pelvic floor recruitment

After both RB and PRB, participants were asked whether they recruited the pelvic floor during the trial. This included whether specific bodily sensations distinct to pelvic floor activation occurred, which were experienced during the introductory training.

2.4 | Procedure

Participants were recruited via social media and gave written informed consent prior to participation, including the information that they could withdraw from the study at any time. Participants were seated in a comfortable chair with their feet parallel to the floor. During the 5-min baseline assessment, a muted video with natural scenes was presented on a screen at eye level. Subsequently, participants were introduced to RB and PRB and executed a brief practice trial for each technique. After the introductory period, participants executed RB and PRB for 5 min each in randomized order, separated by washout periods of 5 min, during which participants were instructed to breath naturally. Also, post breathing trials, participants had to report whether they experienced any symptoms of hyperventilation and/or other non-specific adverse events (Figure 1). Hyperventilation was assessed dichotomously (i.e., Yes/No) via the following items retrieved from the Nijmegen Questionnaire (van Dixhoorn & Duivenvoorden, 1985): Feeling tensed, feeling stiffness in the arms and/or fingers, cold hands and/or feet and dizziness (van Dixhoorn & Duivenvoorden, 1985). The breathing was paced via a moving bar that was visualized on a screen. The breathing pace was set at 0.1 Hz, with an inspiratory phase of 4.0 s and an expiration period of 5.6 s. After both inspiration and expiration, the pacer paused for 200 ms to facilitate a smooth transition from inhalation to exhalation and vice-versa, thus yielding a length of 10 s per breathing cycle. On a general note, participants were instructed to adhere to the following instructions prior to their appointment: No alcohol or strenuous exercise in the 24 hr prior and no exercise, no caffeine, no nicotine intake as well as no fluid and/or food consumption in the 4 hr prior testing (Laborde et al., 2017).

2.5 | Standard resonance breathing (RB)

RB was instructed according to Lehrer et al. (2013), emphasizing rhythmic and abdominal breathing as well as avoiding

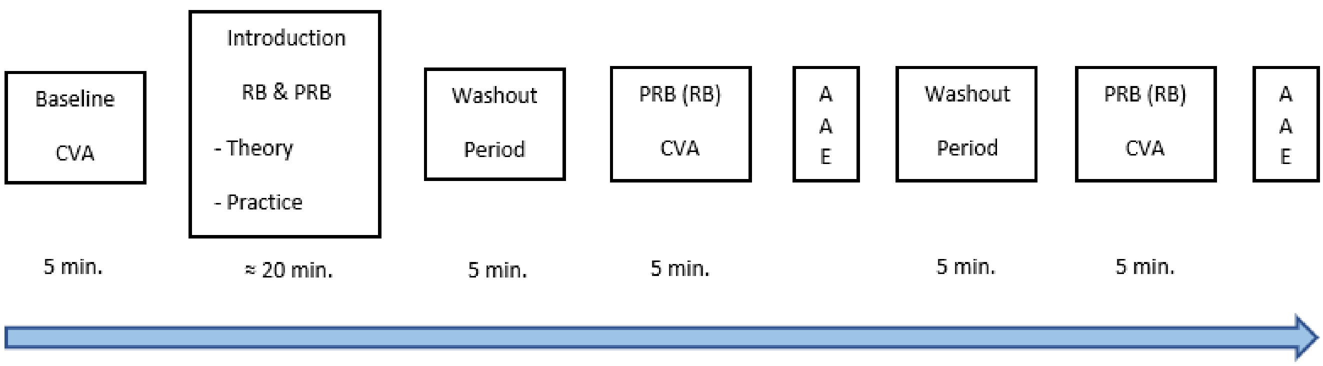

FIGURE 1 Experimental protocol. Breathing trials were executed in randomized order. AAE, assessment of adverse events; baseline, unguided resting respiration; CVA, cardiac vagal activity; PRB, pelvic floor resonance breathing; RB, standard resonance breathing.

hyperventilation based on the findings of Szulczewski (2019). Also, participants were instructed to inhale and exhale nasally instead of the pursed lips breathing technique, to keep the actual breathing exercise as simple as possible.

2.6 | Pelvic floor resonance breathing (PRB)

Following the RB introduction, participants were taught the PRB technique. The first step addressed rehearsing the location of the pelvic floor in the body and its utility. For example, it was explained that during voluntary interruption of the urinary stream, one would activate the pelvic floor. Next, they were taught to intentionally de−/activate the pelvic floor muscles via sex-specific cues (Aljuraifani et al., 2019; Henderson et al., 2013; Stafford et al., 2016). It has been shown that individuals naïve to pelvic floor training can reliably recruit the pelvic floor muscles after a brief verbal introduction (Henderson et al., 2013; Stafford et al., 2015, 2016). Importantly, participants were instructed to keep the rest of the body relaxed during pelvic muscle recruitment. Subsequently, participants were instructed to recruit and release the pelvic floor in coherence with inspiration and expiration. Precisely, the pelvic floor activation should be initiated simultaneously with the beginning of the inhalation, lasting for the entire inspiratory phase, and released abruptly at the initiation of the expiration and ought to stay relaxed till the start of the subsequent inhalation. Additionally, it was emphasized that the pelvic floor de−/activation, analogous to a conductor, should drive the initiation of inspiratory and expiratory cycles to optimize synchronization. The coherence between inspiration and pelvic floor recruitment needs to be stressed as the findings of Bastos et al. (2020) showed HR increases during the activation of the pelvic muscles and decreases after the release, which was independent of respiration. Hence, it can be hypothesized that pelvic muscle recruitment during the expiratory phase might impede rather than strengthen the magnitude of HRV. During the introductory phase, participants were instructed to alternate between low, medium, and maximum intentional pelvic floor activation from 0 (i.e., rest = no recruitment effort) to 10 (i.e., maximum recruitment effort) based on the CR10 Borg scale, which has been shown to index the degree of pelvic floor activation (Stafford et al., 2015, 2016; Williams, 2017). Finally, participants were instructed to recruit the pelvic floor with a mean intensity of approximately 5–6 (i.e., somewhat strong—strong recruitment effort) on the CR10 Borg scale, which ought to be the effort for the actual experimental trial, as subjective intensities of three or higher have been validated to reliably elicit pelvic floor activation (Stafford et al., 2015, 2016; Williams, 2017). Of note, participants were encouraged to avoid excessive (pelvic muscle) effort during the PRB trial as this could yield increased sympathetic arousal, potentially opposing CVA (e.g., Lehrer et al., 2009). At the end of the practice phase, all participants stated that they could successfully execute PRB with the demanded effort, successfully distinguishing between RB and PRB, based on distinct bodily sensations. On a general note, participants were instructed to keep the recruitment effort as constant as possible throughout the PRB trial.

2.7 | Statistical analyses

SPSS (Vers. 27) was used to analyze the data. Separate repeated-measures ANOVAs were conducted for each outcome variable, with condition (i.e., Baseline, RB and PRB) as within-subjects factor and eta-squared as effect size for main effects. Greenhouse–Geisser correction was applied when sphericity was not given. Post hoc pairwise contrasts were assessed via paired t tests, using Cohen's d for effect size estimation, with ds of 0.2, 0.5, and 0.8 defining small, medium, and large effects, respectively (Cohen, 1988). A Bonferroni correction was applied to adjust the alpha level for the planned post hoc t tests (HR, lnRMSSD, lnLF-HR, rel. LF-HRV, breathing rate x three conditions) to $p = .0033$ (i.e., .05/15). Shapiro–Wilk tests were performed to assess the distribution of the variables of interest. Natural logarithmic transformation was conducted for all HRV parameters when normality was violated (Laborde et al., 2017).

3 | RESULTS

3.1 | Data quality

Across the complete sample, three participants showed artifacts during the baseline HRV assessment. In all three cases, the percentage of corrected beats was below one percent (i.e., 0.46%, 0.89%, 0.20%), thus justifying the inclusion of the data. No artifact correction was required during RB and PRB, respectively.

3.2 | Manipulation check

A significant main effect was found for the KUBIOS RRI derived respiratory frequency ($F[2, 62] = 49.513$, $p < .001$, $\eta^2 = .615$). Pairwise contrasts revealed significantly lower breathing rates during both, RB ($t[31] = -8.68$, $p < .001$, $d = 1.54$) as well as PRB ($t[31] = -7.20$, $p < .001$, $d = 1.27$) compared to baseline (13.75 BPM). RB (8.75 BPM) and PRB (9.17 BPM) did not differ significantly from each other

($p = .351$; Table 1). Of note, the main effect for the condition for rel. LF-HRV was observed ($F[1.123, 34.819] = 68.216$, $p < .001$, $\eta^2 = .688$), documenting increasing values from baseline to RB ($t[31] = 8.72$, $p < .001$, $d = 1.54$) as well as to PRB ($t[31] = 8.07$, $p < .001$, $d = 1.43$; Table 1). Importantly, the mean peak spectral power was at 0.1 Hz ($SD = 0.000$) for both RB and PRB. Hence, during both 0.1 Hz breathing trials participants achieved a HRV frequency profile specific and indicative of successful execution of RB (Shaffer & Meehan, 2020; Figure 2). All participants reported successful pelvic floor activation during PRB and no intentional pelvic muscle recruitment during RB. Also, RB and PRB were well tolerated, as only one participant reported an adverse event. Specifically, a female participant reported a feeling of exertion as well as tension of the pelvic floor toward the end of the PRB interval, which however subsided immediately after the trial. Thus, the participant was included in the final analysis, as she reported the successful execution of the PRB technique during the complete trial.

3.3 | Cardiac vagal activity

RMSSD was significantly modified by condition ($F[1.638, 50.777] = 47.415$, $p < .001$, $\eta^2 = .605$). A significantly higher RMSSD during RB ($t[31] = 5.01$, $p < .001$, $d = 0.89$) and PRB ($t[31] = 8.53$, $p < .001$, $d = 1.51$) as compared to baseline was observed. Importantly, PRB induced a significantly incremental increase of RMSSD relative to RB, which was of large effect size ($t[31] = 5.88$, $p < .001$, $d = 1.04$). (Figure 3; Table 1).

Additionally, a main effect for LF-HRV was found ($F[1.336, 41.419] = 113.056$, $p < .001$, $\eta^2 = .785$). Both 0.1 Hz breathing conditions yielded significantly larger LF-HRV than the baseline condition (RB: ($t(31) = 10.10$, $p < .001$, $d = 1.79$; PRB: ($t(31) = 12.04$, $p < .001$, $d = 2.13$). Moreover, PRB induced significantly higher LF-HRV than RB ($t(31) = 4.23$, $p < .001$, $d = 0.75$; Figure 3; Table 1). Finally, no effect of condition on HR was found ($F[1.690, 52.377] = 0.638$, $p = .507$, $\eta^2 = .020$; Table 1). The analysis syntax for the presented results is available at https://osf.io/mhq9j/?view_only=edfa7d3870a54ba79d642d6c28df2905.

4 | DISCUSSION

This study assessed whether coherent pelvic floor activation during 0.1 Hz breathing could boost CVA beyond

TABLE 1 Paired *t* tests for comparisons between conditions

	Baseline	RB	PRB				
	***M* (*SD*)**	***M* (*SD*)**	***M* (*SD*)**	**Contrasts**	***t*(31)**	**|*d*|**	**p***
rHR	70.38 (12.63)	71.32 (10.09)	70.59 (10.07)	ns.			
rRMSSD	42.68 (22.46)	58.95 (27.57)	79.00 (36.99)				
lnRMSSD	3.62 (0.54)	3.97 (0.49)	4.25 (0.52)	RB > Base	5.01	0.89	<.001
				PRB > Base	8.53	1.51	<.001
				PRB > RB	5.88	1.04	<.001
rLF	2344.28 (4016.41)	8553.08 (6532.52)	12,049.08 (8090.48)				
lnLF	6.93 (1.17)	8.77 (0.85)	9.13 (0.83)	RB > Base	10.10	1.79	<.001
				PRB > Base	12.04	2.13	<.001
				PRB > RB	4.23	0.75	<.001
rel. LF	59.32 (20.08)	90.94 (4.69)	88.01 (5.77)				
				RB > Base	8.72	1.54	<.001
				PRB > Base	8.07	1.43	<.001
				PRB = RB	−2.86	.51	.008
rBPM	13.75 (2.81)	8.75 (2.25)	9.17 (2.07)				
				RB < Base	−8.68	1.54	<.001
				PRB < Base	−7.20	1.27	<.001
				PRB = RB	.95	.17	.351

*Bonferroni corrected alpha adjusted to $p = .0033$.

Abbreviations: Baseline, unguided resting respiration; BPM, breaths per minute; HR, heart rate; LF, low-frequency HRV; ln, natural logarithmic normalization of the data; ns., non-significant; PRB, pelvic floor resonance breathing; r, raw values; RB, standard resonance breathing; rel. LF, LF %; RMSSD, root mean square of the successive differences.

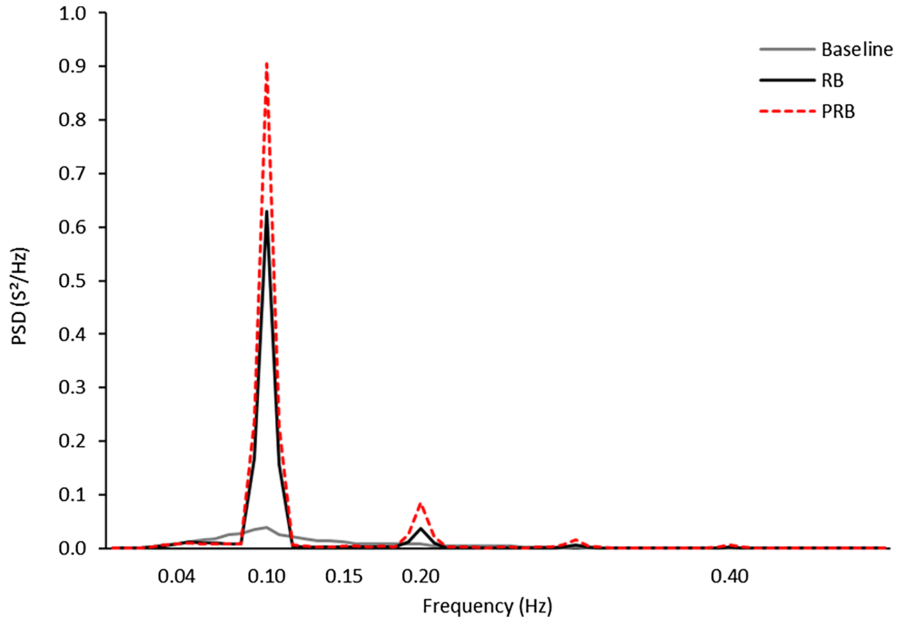

FIGURE 2 Power spectral density averaged across all participants for each experimental condition. Baseline, unguided resting respiration; PRB, pelvic floor resonance breathing; PSD, power spectral density; RB, standard resonance breathing.

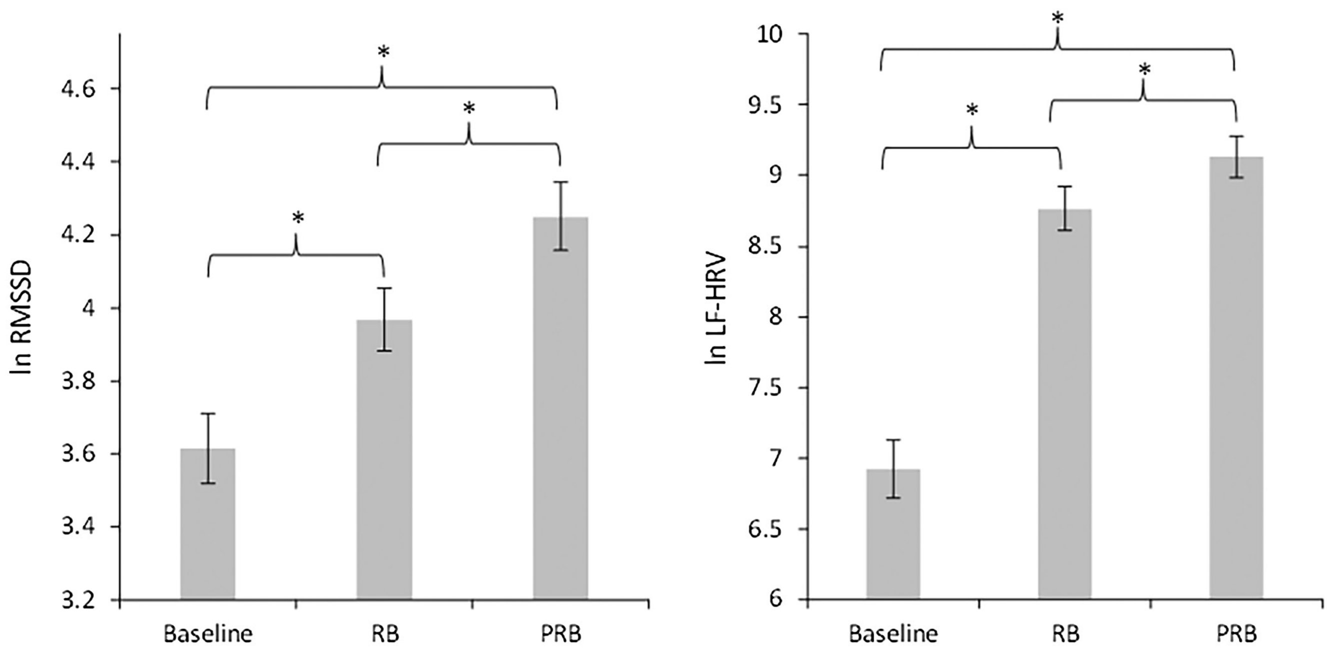

FIGURE 3 Pairwise comparisons between experimental conditions for mean ln RMSSD ± 1*SE* and ln LF-HRV ± 1*SE*. Baseline, unguided resting respiration; PRB, pelvic floor resonance breathing; RB, standard resonance breathing. *Significant differences (*ps* < .001); ln, natural logarithmic transformation; LF-HRV, low-frequency HRV; RMSSD, root mean square of successive differences.

traditional RB. Recent findings emphasize the potential of rhythmical muscle tension to induce cardiac resonance and that pelvic floor recruitment could stimulate the baroreflex (Bastos et al., 2020; da Silva Corrêa et al., 2020; Lehrer et al., 2009; Vaschillo et al., 2011). Accordingly, a cumulative and therefore stronger effect for PRB on CVA compared to RB was expected. Confirming our hypothesis, PRB induced significantly higher RMSSD as well as LF-HRV, thus indicating a significant CVA boosting effect.

Our findings extend prior research aiming at improving the efficacy of RB to augment cardiac vagal control. Noteworthy, the PRB technique could complement methods that specifically alter the breathing pattern during RB. For example, during both RB as well as normal resting respiration, an inspiratory to expiratory ratio (I/E) below 1.0 seems to favor CVA as compared to an I/E of 1.0 or higher (Bae et al., 2021; Laborde et al., 2021; Van Diest et al., 2014). On the contrary, supplementing RB with brief pre- and/or post-expiratory pauses seems to have no noteworthy add-on effect on established markers of CVA during RB, like RSA, RMSSD, and/or LF-HRV (Laborde et al., 2021; Russell et al., 2017). Compared to the inconclusive effects of respiratory pauses, applying respiratory loads during RB, especially inspiratory loading, seems to reliably strengthen CVA evidenced by medium-sized increases in RMSSD and RSA (Gholamrezaei et al., 2019, 2021a, 2021b). Hence, in line with this elegant string of research, our results support the utility of coherent, complementary stimuli to strengthen CVA during RB. Importantly, both approaches seem to exhibit distinct advantages in terms of feasibility, which might facilitate compliance in respective populations. For example, loaded RB should be easier to learn, potentially favoring populations with constrained psycho-motoric abilities. On the contrary, once familiar with PRB, the latter can be practiced without any additional device, which allows its application largely independent of an individual's situational context. Intriguingly, loaded RB and PRB might as well complement each other, since distinct stimuli (i.e., inspiratory loading vs. pelvic floor recruitment) are utilized to generate the observed CVA increments. Hence, using inspiratory resistance in conjunction with PRB might yield even stronger resonance effects than either approach on its own. Of note, a case study showed extremely pronounced RSA when an orthostatic stimulus (i.e., head-down tilt) was combined with very large tidal volumes (Baden et al., 2014). Similar to loaded RB, augmented arterial baroreflex modulation might be pivotal to the PRB effect (Gholamrezaei et al., 2019, 2021a). However, the latter might utilize additional, distinct pathways, compared to inspiratory loading, which has been suggested to be driven primarily by larger blood pressure swings secondary to stronger intra-thoracic pressure modulations (Gholamrezaei et al., 2019, 2021a).

First, PRB might induce its cardiac resonance effects via the associated muscular effort per se as suggested in prior studies utilizing large skeletal muscle groups (e.g., Lehrer et al., 2009; Vaschillo et al., 2011). However, as briefly mentioned earlier, we hypothesize that PRB could exert its effects directly acting on cardiac-pulmonary functioning. For example, it has been shown that the pelvic floor plays an important, though to date largely neglected role in respiration and that voluntary pelvic muscle activation could further enhance breathing capacity (Gordon & Reed, 2020). Specifically, intentional pelvic floor recruitment has been shown to increase maximum voluntary ventilation, which might be attributed to strengthened activation of the diaphragm (Park et al., 2015; Park & Han, 2015). Noteworthy, this seems to be due to increased breathing velocity rather than due to tidal volume increments, as forced vital capacity, although slightly smaller on a descriptive level during pelvic activation, was not significantly affected by the latter (Park & Han, 2015). Increased intra-abdominal pressure during pelvic floor activation seems to decrease diaphragmatic descent, potentially neutralizing the effect of increased respiratory muscle force on tidal volume generation (Neumann & Gill, 2002; Park et al., 2015; Park & Han, 2015). Hence, it could be hypothesized that increased tidal volume, which is linked to HRV augmentation during slow-paced breathing, is not the main driver of the PRB effect (Grossman & Taylor, 2007). Yet, as compared to RB, PRB could induce a steeper inspiratory curve via a more forceful initiation of inhalation, which has been suggested to yield stronger baroreflex modulation, ultimately augmenting HR oscillations (Heesch, 1999; Strauss-Blasche et al., 2000). It needs to be mentioned though, that the latter, at least to a certain degree, might be attributed to a stronger sympathetic modulation during a more forceful inspiration (Strauss-Blasche et al., 2000). However, as shown by Kromenacker et al. (2018) via para−/sympathetic blockade, HRV during RB originates predominantly from cardiac vagal efferent control. Still, to gain clarity regarding this issue, subsequent studies should include the pre-ejection period as a measure of cardiac sympathetic modulation (Cacioppo et al., 1994; Sherwood et al., 1990). Additionally, PRB could increase cardiac venous return via an additional increase in intra-abdominal pressure within a functional spectrum, transferring to augmented stroke volume and, in turn, boosting CVA following stronger baroreflex stimulation (Balzan et al., 2014; Kitano et al., 1999; Russo et al., 2017; Takata et al., 1990; Takata & Robotham, 1992). Noteworthy, reducing diaphragmatic descent, PRB might yield a more pronounced thoracic breathing amplitude as compared to RB, thus manifesting in a stronger rib cage expansion, which could foster negative intrathoracic pressure and therefore, baroreflex modulation (e.g., Convertino et al., 2011; Park & Han, 2015; Uva et al., 2016). Of note, the absence of alterations in mean HR between baseline, RB and PRB, emphasizes that the latter amplifies the phasic cardiac vagal efferent control (i.e., CVA) rather than vagal tone, similar to loaded RB (Gholamrezaei et al., 2019, 2021a; Grossman & Taylor, 2007). Thus, the PRB effect could largely originate from baroreflex-driven CVA increments via shared (i.e., intra-thoracic pressure modulations) as well as distinct pathways compared to loaded RB (Gholamrezaei et al., 2019, 2021a). Hence, «loaded PRB» might indeed generate additional increments on baroreflex-mediated CVA, as indicated by dose-dependent responses to mechanical stimulation (i.e., neck chamber), which however could be limited due to a potential ceiling effect (Seredyński et al., 2021). However, as the hypothesized superimposed CVA boost could rely on the non-baroreflex-mediated contribution of pulmonary afferents, the loaded PRB hypothesis might as well be falsified, warranting within-subjects design studies comparing the respective techniques (Baden et al., 2014). Of note, the latter could elucidate whether the larger CVA increments due to PRB compared to those observed by Gholamrezaei et al. (2019, 2021a) in response to loaded RB, are a function of the technique per se or related to sample characteristics and/or factors like breathing technique (i.e., oral vs. nasal). To conclude, it can be hypothesized that PRB seems to strengthen functional respiratory-cardiac interactions, which intrinsically occur across the breathing cycle, ultimately amplifying CVA.

It is worth mentioning in this regard that recent evidence suggests RB-driven amplification of HR oscillations as a potent neuromodulator, as two recent studies report increased functional connectivity within brain networks related to emotion and cardiac regulation, after several weeks of biofeedback-guided RB (Nashiro et al., 2021; Schumann et al., 2021). Noteworthy, Nashiro et al. (2021) showed that biofeedback guided RB enhanced functional connectivity between the medial prefrontal cortex and the left amygdala at rest as well as improved downregulation of somatosensory centers during exposure to emotional pictures, which indicates improved implicit emotion regulation. In comparison, a sham biofeedback condition targeting HR to be constant rather than oscillatory had no such effects, which suggests that the amplification of HRV and not necessarily the contemplative effort during RB seems to drive its mental−/health bolstering effects (Nashiro et al., 2021). Therefore, it can be hypothesized that PRB could strengthen the brain entraining effects of RB via inducing stronger increments in HRV, potentially yielding stronger therapeutic effects (Lehrer et al., 2020; Tatschl et al., 2020). Consequently, future research should implement brain imaging methods to elucidate potential differences between PRB and RB on cerebral functioning, including longitudinal designs. In this regard, HRV biofeedback could be advantageous relative to paced RB as it would allow to optimally adapt the recruitment intensity of the pelvic floor to maximize HRV (Tatschl et al., 2020).

It should be noted that several factors could moderate the efficacy of PRB. First, young and healthy individuals (as in the present sample) are likely to exhibit stronger effects than health compromised and/or older populations. For example, pelvic floor strength as well as the degree of its activation could moderate its effects on diaphragmatic function as well as on generating pressure modulations (Gordon & Reed, 2020). Therefore, as pelvic floor functionality seems to decline with age as well as in individuals suffering from anxiety and depression, weaker acute effects might be observed in these populations (Trowbridge et al., 2007; Vrijens et al., 2017; Wente & Dolan, 2018). On the contrary, physical fitness is positively linked to pelvic floor strength, thus suggesting that athletes who have been utilizing RB to improve performance might experience a particularly strong CVA boost due to PRB (Jürgensen et al., 2017; Lehrer et al., 2020; Pagaduan et al., 2020). Hence, the magnitude of acute effects on CVA is likely moderated by an individual's psychophysiological integrity, potentially requiring regular practice in respective populations to achieve comparable CVA boosting effects as observed in the present study. Importantly, a brief 5-min bout of PRB was well tolerated in our sample, which is in line with the high safety profile of pelvic muscle training reported in the literature (Dumoulin & Hay-Smith, 2010). Yet, in the context of a potential PRB practice, analogous to strength training, session frequency, duration as well as intensity should be carefully gauged to optimize its effectiveness as well as to avoid any aversive effects, that may occur due to excessive pelvic muscle exertion (Bø, 2009). In general, the balanced female to male ratio in the present study indicates minor sex-specific effects of PRB, which however needs to be validated in larger powered replication studies.

4.1 | Limitations

Despite the promising findings of the present study, several limitations need to be addressed. First, no direct physiological marker of pelvic floor activation was assessed and therefore, follow-up studies should aim to objectively quantify pelvic floor activity to control for the moderating effect of applied muscle force. Second, the RRI-derived breathing rate estimation yielded slightly higher rates than 0.1 Hz. Still, this is likely due to an overestimation of the respiratory rate by the KUBIOS algorithm as recently suggested (Lipponen & Tarvainen, 2021). Accordingly, breathing compliance seems to have been reasonable, considering that during both RB and PRB the prototypic frequency HRV pattern was observed (Shaffer & Meehan, 2020; Figure 2). However, future studies should strive for a thorough assessment of respiration via spirometry and breathing belts (Miller et al., 2005). This would allow to elucidate distinct differences in the respiratory pattern between PRB and RB, including tidal volume, respiratory gradient as well as end-tidal CO_2, and abdominal/thoracic breathing, which could drive the additional CVA boost of PRB (Grossman & Taylor, 2007; Heesch, 1999; Miller et al., 2005; Strauss-Blasche et al., 2000). Third, hemodynamic assessment including continuous blood pressure is imperative for future studies to validate whether the hypothesized effects of PRB on the baroreflex can be verified (Gholamrezaei et al., 2019, 2021a). Fourth, this study did not account for the link between physical fitness and pelvic floor strength, which, as described earlier, could play an important role regarding the efficacy of PRB (Jürgensen et al., 2017; Sapsford & Hodges, 2001; Zachovajeviene et al., 2019). Hence, physical fitness should be assessed as a potential moderator in future studies. Finally, the effects of PRB on psychological functioning, an important application of RB, should be targeted in subsequent research, which has not been addressed in this first study (Lehrer et al., 2020).

5 | CONCLUSION

To conclude, our findings support recent research that complementing RB with additional techniques could strengthen CVA. In that sense, utilizing the pelvic floor as a supplementary stimulus during RB seems to provide a strong CVA boost, thus extending prior findings emphasizing respiratory patterns and resistance breathing. Importantly, PRB seems highly feasible as it can be utilized independently of technical devices as required with loaded RB. Thus, PRB could provide a simple tool to advance the resonance breathing paradigm, potentially contributing to stronger treatment effects. In that regard, further studies are warranted to validate the PRB technique within distinct populations including athletes and clinical samples. Finally, longitudinal research is certainly warranted to examine the potential benefits of this technique on mental and physical health as well as performance.

AUTHOR CONTRIBUTIONS

Josef Martin Tatschl: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; resources; software; visualization; writing – original draft; writing – review and editing. **Andreas Richard Schwerdtfeger:** Resources; supervision; writing – review and editing.

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CONFLICT OF INTEREST

The authors declare that they have no conflict of interest.

ORCID

Josef Martin Tatschl https://orcid.org/0000-0003-1594-1770
Andreas Richard Schwerdtfeger https://orcid.org/0000-0002-0371-3730

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