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RESEARCH ARTICLE

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Understanding mind–body disciplines: A pilot study of paced breathing and dynamic muscle contraction on autonomic nervous system reactivity

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Abstract
Mind–body disciplines such as yoga, Tai Chi, and Qigong have been demonstrated to activate the parasympathetic nervous system, but it remains unclear how these practices achieve these results, whether by breathing, movement, or some combination. This pilot study establishes a model to examine the individual and combined effects of paced breathing and rhythmic skeletal muscle contraction on the activation of the parasympathetic system during a cognitive stressor. Male participants were randomly assigned to one of four preconditioning groups: (a) paced breathing alone, (b) alternating upper extremity muscle contractions, (c) paced breathing synchronized with alternating contractions, or (d) a neutral control task. Autonomic response was assessed by heart rate variability during a standardized cognitive stressor. The alternating contraction group had 71.7% higher activation of parasympathetic signal over respiration alone ($p < .001$). Alternating contractions synchronized with breathing demonstrated 150% higher parasympathetic activation than control ($p < .0001$). Comparing the contraction alone and synchronized groups, the synchronized group demonstrated 45.9% higher parasympathetic response during a cognitive stressor ($p < .001$). In conclusion, paced breathing synchronized with rhythmic muscle contraction leads to more resilient activation of the parasympathetic response than either alternating contractions or breathing alone, which may help explain the stress reducing benefits of mind–body disciplines.

KEYWORDS
biological mechanisms of stress, cardiovascular reactivity, psychophysiology, respite/recovery resilience, stress, mindfulness, stress management

1 | INTRODUCTION

Recent focus on stress reduction and physiological resiliency has led to further interest in the autonomic nervous system's adaptation to stress. Many popular mind–body practices such as yoga, Tai Chi, and Qigong have been shown to activate the parasympathetic nervous system (Goyal et al., 2014; Sullivan et al., 2018; Walther, Lacker, & Ehlert, 2018). Paced respiration and dynamic tension through rhythmic skeletal muscle contraction are two core components common to yoga, Tai Chi, and Qigong; however, it remains unclear by which mechanisms these training disciplines activate the parasympathetic nervous system. Therefore, without understanding the interaction between breathing and movement, it is challenging to optimize the benefits of these practices. This pilot study establishes a model to examine the individual and combined effects of paced breathing and rhythmic skeletal muscle contraction.

Paced breathing is a technique with a proposed mechanism of action that is mediated through the activation of the body's parasympathetic nervous system through entrainment effects between respiratory rate and heart rate (Jerath, Edry, Barnes, & Jerath, 2006; Nijjar et al., 2014). Although the exact respiratory frequency may vary slightly from person to person, studies have demonstrated that the resonant breathing frequency is around 0.1 Hz, or one breath cycle every 10 s (Lehrer, Vaschillo, & Vaschillo, 2000; Lin, Tai, & Fan, 2014).

Less recognized and understood, concurrent evidence also suggests that voluntary rhythmic muscle contraction alone could be an alternative way of stimulating the parasympathetic nervous system. In a study on rhythmic contraction alone, Lehrer et al. demonstrated that when large muscle groups alternated rhythmically between contraction and relaxation, subjects experienced a similar parasympathetic entrainment effect observed in the earlier paced breathing studies (Lehrer, Vaschillo, Trost, & France, 2009; Vaschillo, Vaschillo, Pandina, & Bates, 2011). However, the autonomic effects of performing rhythmic synchronized breathing and muscle contraction tasks simultaneously have not been studied systematically. Understanding the synergistic effect between these components may help to explain the observed benefits many practitioners experience after various types of mind–body training.

Additionally, practice of mind–body disciplines has been demonstrated to improve cognitive function. Three meta-analyses have shown that training in yoga, Tai-chi, and Qigong led to improved cognitive function in older populations (Chan, Deng, Wu, & Yan, 2019; Wayne et al., 2014; Wu et al., 2019). However, the mechanism of how these practices achieve these effects has not been established. Considering that these disciplines are partly meditative arts, short-term studies have suggested that meditation can have near immediate positive effects on task performance (Chan, Immink, & Lushington, 2017; Chan, Lushington, & Immink, 2018; Colzato, Sellaro, Samara, & Hommel, 2015; Colzato, van der Wel, Sellaro, & Hommel, 2016).

Using established heart rate variability (HRV) measures to determine the autonomic state, the first aim of this study will address whether entrainment with rhythmic muscle contraction synchronized with respiration at a resonant frequency can produce greater activation of the parasympathetic system more effectively than either technique alone when challenged with a cognitively induced sympathetic state. Second, this study will evaluate whether the type of preconditioning affects task performance.

2 | METHODS

2.1 | Participants

Because HRV changes have been shown to vary differently between males and females due to hormonal differences, only males were recruited for this pilot study to minimize variation (Koenig & Thayer, 2016; Sato & Miyake, 2004). Forty-eight healthy male participants, ages 18–55, were recruited and consented from Harvard T.H. Chan School of Public Health- and Harvard Medical School-affiliated student programs, fellowships, and training residencies. An initial telephone screening interview was performed for all participants. Individuals with any history of restrictive or obstructive lung disease, hypertension, or taking any medications that could alter blood pressure were excluded. Although participants using prescription stimulants were excluded from the study, caffeine consumption was not specifically restricted as it has been shown that withdrawal effects on HRV may exist for habitual caffeine users (Zimmermann-Viehoff et al., 2016). The study protocol was reviewed and approved by the IRB of the Harvard T.H. Chan School of Public Health.

The participants were randomized prior to the testing session to one of four preconditioning groups using the online Research Randomizer tool (www.randomizer.com). Preconditioning groups were (a) diaphragmatic breathing at 0.1 Hz (inhale nose 5 s, exhale mouth 5 s) for 5 min, (b) rhythmic contraction and relaxation of arm muscles by grasping a tennis ball at 0.1 Hz for 5 min (alternating contractions in left and right arms every 5 s), (c) performing synchronized diaphragmatic breathing and contractions at 0.1 Hz for 5 min, and (d) a control group assigned to read four adapted articles from Scientific American that were rated as emotionally neutral for 5 min (van den Broek, Lorch, Linderholm, & Gustafson, 2001).

2.2 | Testing procedure

All testing occurred over a 30-min session with only the experimenter and participant present in a quiet room between the daytime hours of 09:00 and 16:00. After written informed consent was obtained, a Polar H7 heart rate monitor (Polar Electro Oy, Kempele, Finland) was then placed at the participant's mid-chest level. The Polar chest strap systems have already been validated as a reliable research device measuring heart rate with accuracy comparable with electrocardiograms used in clinical medicine by measuring R-R intervals at a sampling rate of 1000 Hz (Barbosa, da Silva, de Azevedo, Pastre, & Vanderlei, 2016; Giles, Draper, & Neil, 2016). The R-R interval is the beat-to-beat interval as measured between peaks of consecutive QRS complexes on electrocardiogram. A recording application on iPad (Apple Inc., Cupertino, CA, United States) recorded the R-R intervals from the chest strap, which were analysed offline.

Participants were instructed to sit upright quietly for 5 min while reading the study instructions, and then, baseline heart rate, cuff blood pressure, and respiration rate were obtained. A 5-min period of the assigned preconditioning task was then performed with a graphical timer application on iPad was used to visually cue the initiation and completion of each cycle of breathing or contraction, depending on the group assignment.

Immediately after the preconditioning task, a computerized version of the Stroop test (http://cognitivefun.net) was then run for 5 min to provoke a sympathetic response. The Stroop test has been demonstrated to produce a mild sympathetic response measured by HRV through dissonant executive task function (Salahuddin, Cho, Jeong, & Kim, 2007; Visnovcova et al., 2014). The program automatically performed the test by presenting words written in colour text, and participants were asked to indicate the colour of the word (and not its meaning) by key stroke as fast as possible while minimizing errors. A reaction time for each word pair was recorded by the computer program. The premise of the Stroop test is that incongruent pairs have longer reaction times when compared with congruent pairs (Dyer, 1973). As a marker for performance, a reaction time gap was calculated for each participant from the difference between congruent and incongruent pair reaction times.

For validation of Stroop engagement across groups, at the end of this task period, a 5-min questionnaire (Short Flow State Scale) was then administered to assess degree of task immersion for all groups (Jackson, Martin, & Eklund, 2008). Flow state is the degree of perceived immersion in the task. The Short Flow State Scale has been validated for evaluation of performance engagement. Respiration rates were monitored during all phases of testing to ensure they were within the 9–24 cycles per minute range required for high frequency (HF) to correspond accurately to vagal tone (Laborde, Mosley, & Thayer, 2017).

2.3 | HRV analysis

High frequency (HF) and low frequency (LF) HRV components are reflective of parasympathetic and sympathetic activation, respectively. As a corollary, the ratio LF/HF is generally regarded as the overall sympathovagal balance and degree of autonomic excitement (Shaffer & Ginsberg, 2017). Recorded R-R intervals from the Polar H7 chest strap were downloaded and analysed using Kubios HRV Premium software (Kubios Oy, Kuopio, Finland). The software converted the R-R intervals into frequency domain indices: LF power (ms^2), HF power (ms^2), and LF/HF ratio. Each of the indices was calculated over 2-min intervals based on recommendations from published standards. It is generally accepted that 1 min is needed to assess the HF component of HRV whereas approximately 2 min are needed to address the LF component (Laborde et al., 2017).

For each participant, the baseline and Stroop HRV recordings were processed by Kubios HRV Premium. Automated artifact correction was performed for all recordings prior to analysis. One hundred twenty-second sampling periods were utilized to derive LF, HF, and LF/HF using fast Fourier transformation spectrum method (Figure 1). LF and HF bands were standardly defined as 0.04–0.15 and 0.15–0.4 Hz, respectively, and absolute power for each band was analysed in normalized units, LF or HF divided by total power (Malliani, Lombardi, & Pagani, 1994). The Stroop HRV measurements were normalized to each participant's baseline. Normalized Stroop HRV indices for each preconditioning group were compared by one-way ANOVA with Tukey's post-hoc test.

3 | RESULTS

All enrolled participants (n = 48) completed the study sessions without any adverse events. Participants' average age, resting blood pressure, heart and spontaneous respiration rates are summarized in Table 1. As a result of randomization, 12 subjects were assigned to the control group, and 12 subjects were assigned to each preconditioning group.

3.1 | Parasympathetic response (HF)

ANOVA for HF demonstrated significant changes between groups (F (3,44) = 32.85, p < .0001; Figure 2a). During administration of the Stroop test, there was no significant difference between breathing alone group and reading control. The alternating contraction group had 71.7% higher activation of HF over respiration alone (p < .001). Alternating contractions synchronized with breathing demonstrated 150% higher HF activation than control (p < .0001). Between contraction alone and combined contraction groups, the combined group demonstrated 45.9% higher HF response (p < .001).

3.2 | Sympathetic response (LF)

ANOVA for LF demonstrated significant changes between groups (F (3,44) = 8.258, p < .001; Figure 2b). Sympathetic activation during administration of the Stroop test was not different between the breathing alone group and reading control. The alternating the contraction group and synchronized groups had 33.5% and 45.2% lower LF HRV activation than control, respectively (p < .01 and p < .0001). There was no significant difference in LF response between the contraction alone and synchronized groups.

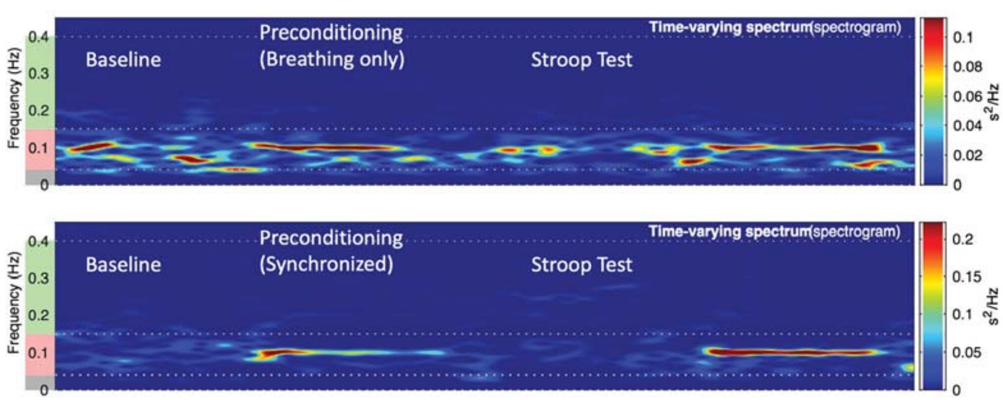

FIGURE 1 Examples of heart rate variability (HRV) data after frequency analysis. After R-R interval data were processed in Kubios HRV Premium, fast Fourier transformation spectral analysis was performed separating the HRV power into low frequency (LF) and high frequency (HF) components. For comparison, the autonomic state during the Stroop test was normalized to baseline reading for each subject

TABLE 1 Baseline characteristics

Group	Mean age	Mean systolic BP	Mean diastolic BP	Mean HR	Mean R-R
Breath Only	29.7	121.8	76.2	69.0	16.9
n=12	(22–40)	(97–136)	(70–88)	(52–95)	(10–25)
Contraction Only	26.7	121.5	73.2	69.9	18.8
n=12	(22–33)	(104–136)	(61–86)	(57–82)	(15–24)
Breath and Contraction	32.3	120.1	74.8	67.3	16.4
n=12	(22–38)	(107–134)	(68–88)	(55–83)	(9–26)
Control	30.3	122.7	79.7	63.7	16.2
n=12	(22–46)	(102–145)	(63–96)	(53–81)	(8–25)

Abbreviations: BP = Blood Pressure, HR = Heart Rate, RR = Respiration Rate

3.3 | Sympathovagal response (LF/HF)

ANOVA for LF/HF demonstrated significant changes between groups ($F(3,44) = 10.62$, $p < .0001$; Figure 2c). Sympathovagal balance results mirrored the sympathetic activation. There was no significant LF/HF ratio difference between the breathing alone group and the reading controls. Similar to LF, both contraction groups had significantly lower LF/HF over control, respectively ($p < .01$ and $p < .001$). Again, similar to LF, there was no significant difference in LF/HF response between the contraction alone and synchronized groups.

3.4 | Cognitive performance and engagement

There were no differences for Stroop test reaction time among groups ($F(3,44) = 1.359$, $p > .05$). Similarly, there were no significant differences between Short State Flow State scores among the four preconditioning groups ($F(3,44) = 1.172$, $p > .05$; data not shown).

4 | DISCUSSION

Despite the widespread adoption of various mind–body practices such as yoga, Tai Chi, and Qigong, there still lacks consensus regarding how these disciplines produce their powerful benefits (Riley & Park, 2015). The Respiratory Vagal Stimulation Model hypothesizes that these disciplines confer benefits through attentively regulated breathing (Gerritsen & Band, 2018). However, this theory ignores another key component of these mind–body disciplines, muscle contraction. Our pilot study provides a simplified model to study the combined effects between two fundamental, common elements of these practices: respiration and muscle contraction. Our results suggest that cyclic respiration synchronized with alternating muscle contraction may be one underlying phenomenon that confers increased parasympathetic balance.

Contrary to the common preconception that breathing practices lead to stress reduction, it is interesting to note that priming with paced respiration alone did not confer lasting increased HRV reactivity during the stress event. Although current research has commonly associated mindful breathing practices with reduction in stress, these results are usually after weeks of training and may be due to post-event stress recovery rather than pre-event priming (Goyal et al., 2014; Wolever et al., 2012). Our results suggest that there may be a distinction between pre-event priming for a stressful event and stress mitigation, wherein entrainment of the autonomic system with synchronized respiration and contraction lead to a more resilient reponse than either component alone.

The powerful priming effect observed when combining cyclic respiration with muscle contraction supports the “bottom-up” polyvagal theory proposed by Stephen Porges (Sullivan et al., 2018). This theory hypothesizes that autonomic regulation is possible through interoception (i.e., an awareness of the internal state of the body's systems) and self-regulatory skills (Gard, Noggle, Park, Vago, & Wilson, 2014). The finding that entrainment with breathing synchronized rhythmic muscle contraction activates the parasympathetic relaxation response more effectively than either one alone could be explained by this process of enhanced interoception. Indeed, movement disciplines such as the Russian martial art Systema may have empirically developed an optimized priming process through highly coordinated rhythmic movement and respiration exercises (Vasiliev, Meredith, & Ryabko, 2006).

When assessing level of task immersion through the flow questionnaire, we observed that there were no differences in level of task engagement among all four groups. This is not unexpected as engagement is dependent on many individual factors such as level of proficiency, personal interest, as well as personality characteristics (Keller & Bless, 2008).

4.1 | Study limitations

Our pilot study represents a relatively small sample. Studies have demonstrated that estrogen levels may affect HRV during the stress response (Koenig & Thayer, 2016; Sato & Miyake, 2004; Thayer, Ahs, Fredrikson, Sollers, & Wager, 2012). Due to these concerns, we restricted our participant enrollment to male participants to minimize hormonal variability, and therefore, we may have limited generalizability to females. Future studies should validate our findings in a female population.

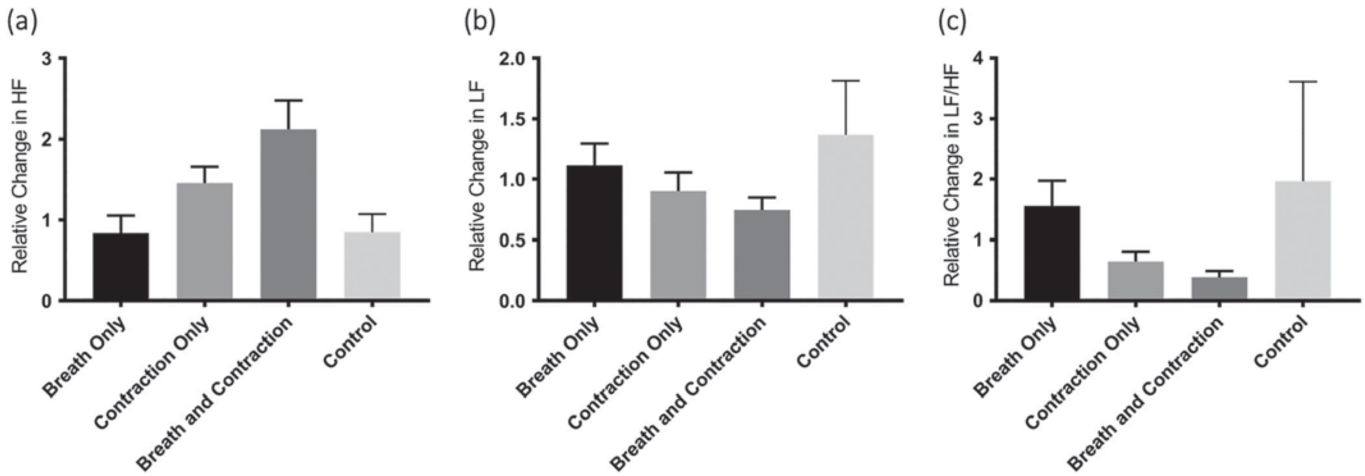

FIGURE 2 (a) Parasympathetic response (high frequency [HF]). There was no significant difference in HF between breathing alone group and reading control during the Stroop test. Alternating contraction group had 71.7% higher activation of HF heart rate variability (HRV) over respiration alone ($p < .001$). Alternating contractions synchronized with breathing demonstrated 150% higher parasympathetic activation than control ($p < .0001$). Between the contraction alone and synchronized groups, the synchronized group demonstrated 45.9% higher parasympathetic response ($p < .001$). (b) Sympathetic response (low frequency [LF]). LF activation during administration of the Stroop test did not demonstrate a difference between breathing alone group and reading control. The alternating contraction group and synchronized groups had 33.5% and 45.2% lower LF activation over control respectively ($p < .01$ and $p < .0001$). There was no significant difference in LF response between contraction alone and synchronized groups. (c) Sympathovagal balance (LF/HF). There was no significant LF/HF ratio difference between breathing alone group and reading control. Both contraction groups had significantly less sympathetic activation over control respectively ($p < .01$ and $p < .001$). There was no significant difference in LF response between contraction alone and synchronized groups

4.2 | Future directions

Although no differences in flow engagement were found between the preconditioning groups, we propose that future studies should examine how these synchronized respiration and contraction patterns may enhance cognitive performance under stress by varying the autonomic response. These findings may be highly relevant for workers who need to make quick and accurate decisions in high stress environments. Real-time management of stress could lead to improved performance under pressure as suggested by a large-scale study of emergency medical responders, where increased perceived anxiety was correlated with patient safety events and compromised decision making (Guise et al., 2017).

5 | PRACTICAL IMPLICATIONS

- Alternating isometric muscle contraction can help to prepare for a stressful event.
- Synchronizing isometric muscle contraction with paced breathing leads to an even more resilient relaxation response in preparation for a stressful event.
- Using rhythmic breathing alone before a stressful event does not lead to a lasting relaxation response.

6 | CONCLUSIONS

Entrainment using paced breathing synchronized with rhythmic skeletal muscle contraction at 0.1 Hz produces a more resilient parasympathetic response than either breathing or muscle contraction alone during a stressful task. Preconditioning type does not appear to lead to significant differences in reaction time performance or task flow immersion.

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CONFLICT OF INTEREST

The authors have declared that they have no conflict of interest.

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