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An Undergraduate Program with Heart: Thirty Years of Truman HRV Research

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Abstract
This article celebrates the contributors who inspired Truman's heart rate variability (HRV) research program. These seminal influences include Robert Fried, Richard Gevirtz, Paul Lehrer, Erik Peper, and Evgeny Vaschillo. The Truman State University Applied Psychophysiology Laboratory's HRV research has spanned five arcs: interventions to teach diaphragmatic breathing, adjunctive procedures to increase HRV, HRV biofeedback (HRVB) training studies, the concurrent validity of ultra-short-term HRV measurements, and rhythmical skeletal muscle tension strategies to increase HRV. We have conducted randomized controlled trials, primarily using within-subjects and mixed designs. These studies have produced eight findings that could benefit HRVB training. Effortful diaphragmatic breathing can lower end-tidal CO2 through larger tidal volumes. A 1:2 inhalation-to-exhalation (I/E) ratio does not increase HRV compared to a 1:1 I/E ratio. Chanting "om," listening to the Norman Cousins relaxation exercise, and singing a fundamental note are promising exercises to increase HRV. Heartfelt emotion activation does not increase HRV, enhance the effects of resonance frequency breathing, "immunize" HRV against a math stressor, or speed HRV recovery following a math stressor. Resonance frequency assessment achieved moderate ($r = 0.73$) 2-week test-reliability. Four weeks of HRVB training increased HRV and temperature, and decreased skin conductance level compared with temperature biofeedback training. Concurrent-validity assessment of ultra-short-term HRV measurements should utilize rigorous Pearson r and limits of agreement criteria. Finally, rhythmical skeletal muscle tension can increase HRV at rates of 1-, 3-, and 6-cpm. We describe representative studies, their findings, significance, and limitations in each arc. Finally, we summarize some of the most interesting unanswered questions to enable future investigators to build on our work.

Keywords Biofeedback · Heart rate variability · Resonance frequency · Rhythmic skeletal muscle tension · Wearables

How I Became Involved in HRV and HRVB Research

I became involved with research in heart rate variability (HRV) and HRV biofeedback (HRVB) when Erik Peper introduced me to effortless breathing through several workshops and became a valued research collaborator. Robert Fried's Association for Applied Psychophysiology and Biofeedback (AAPB) capnometry workshop and prolific writing deepened my appreciation of "low-and-slow breathing" and the importance of breathing chemistry. Paul Lehrer and Richard Gevirtz's HRVB workshops were revelatory and raised fascinating questions that stimulated the next three decades of Truman's undergraduate research. Finally, the late Evgeny Vaschillo's (2018) Distinguished Scientist address at the 49th annual AAPB meeting inspired our rhythmical skeletal muscle tension systematic replication and disassembly studies.

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Review the Research and Findings from Your Lab and Your Students. How Has Your Work Contributed to the General Thrust of Research and Clinical Applications?

The Truman State University Applied Psychophysiology Laboratory's HRV research program has spanned five arcs: (1) interventions to teach diaphragmatic breathing (DB), (2) adjunctive procedures to increase HRV, (3) HRVB training studies, (4) the concurrent validity of ultra-short-term HRV measurements, and (5) rhythmical skeletal muscle tension (RSMT) strategies to increase HRV. We have conducted randomized controlled trials (RCTs) with undergraduate participants, primarily using within-subjects (w/s) and mixed designs. These studies monitored ECG with a lower torso placement. We centered the reference over the angle of the sternum and the active electrodes about 5 cm above the navel and 10 cm to the left and right of the midline. We monitored respiration using a capnometer and respirometer. A resting baseline (BL), in which participants sat quietly without breathing instructions or feedback, was a control condition in many of our studies. Except for the RSMT studies, participants sat upright in a straight-backed chair and placed their feet on the floor. See Table 1 for important terms and definitions.

Interventions to Increase Diaphragmatic Breathing

The DB studies investigated the impact of overbreathing on end-tidal CO2 (ETCO2), respiration rate (RR), respiratory exchange ratio (RER; the volume of CO2 removed from the body divided by the volume of O2 consumed), and tidal volume (TV), and the effects of inhalation-to-exhalation (I/E) ratios on HRV.

Breathing Effort Depresses End-Tidal CO2 (ETCO2)

In this w/s RCT ($N=50$), Shaffer and colleagues (1998) taught participants to breathe diaphragmatically in two 60-min sessions. We assigned participants to 3-min low-effort, rest, high-effort or high-effort, rest, low-effort conditions. We seated participants with eyes open and stabilized them for 5 min before recording data. A breathing model demonstrated diaphragmatic breathing, in which they inhaled through their nostrils in both effort conditions. The low-effort instructions encouraged passive stomach excursion; the high-effort script promoted more forceful abdominal movement. Participants did not receive feedback. A SensorMedics 2900 Metabolic Cart measured ETCO2 and ETCO2 variability. ETCO2 decreased, and ETCO2 variability increased from low to high breathing effort. This study demonstrated that diaphragmatic breathing should be "effortless" (e.g., like smelling a flower; Khazan, 2019) to better conserve CO2.

Effortful Breathing May Lower End-Tidal CO2 Through Increased Tidal Volume

In this w/s RCT ($N=15$), Shaffer and colleagues (1999) replicated the preceding study and measured ETCO2, RER, RR, and tidal volume using the SensorMedics 2900 Metabolic Cart. Participant RR decreased, TV increased, and the RER increased from low to high breathing effort—signaling greater CO2 elimination. TV accounted for 43% of RER variance. These findings indicated that more effortful breathing reduced CO2 by overcompensating through larger TVs.

Does Inhalation-to-Exhalation Ratio Matter in HRVB?

In this w/s RCT ($N=26$), Zerr and colleagues (2015) assigned participants to one of two orders of 6-bpm breathing for 5 min at 1:1 and 1:2 I/E ratios guided by a visual pacing display. A 5-min buffer period separated the breathing trials to minimize carryover effects. The participants sat upright with their eyes open. The researchers confirmed compliance with the RR and I/E ratio instructions by measuring the mean RR and visually inspecting each respiratory cycle's inhalation and exhalation phases. I/E ratio did not affect time-domain (HR Max-HR Min, pNN50, RMSSD, SDNN) or frequency-domain (VLF, LF, and HF power) metrics.

A 1:2 Inhalation-to-Exhalation Ratio does not Increase HRV During 6-bpm Breathing

In this w/s RCT ($N=16$), Meehan and colleagues (2018) replicated the Zerr and colleagues (2015) experiment using a shorter 3-min buffer period to mitigate carryover effects. They confirmed compliance with the RR and I/E ratio instructions as in the previous study. The I/E ratio did not affect autonomic (HR, SCL, TEMP), HRV time-domain (HR Max—HR Min, NN50, pNN50, RMSSD), frequency-domain (LFnu), or nonlinear measurements (DFalpha1, SampEn). This study expanded the prior Zerr and colleagues' findings to demonstrate that the I/E ratio did not affect autonomic and nonlinear metrics.

DB Studies Summary

The overbreathing studies confirmed the importance of effortlessness and ETCO2 monitoring during DB training. We recommend that future investigators objectively

Table 1 Important terms and definitions

Term	Definition
Approximate entropy (ApEn)	The regularity and complexity of a time series
Blood pressure (BP)	The force exerted by circulating blood on arterial walls
Correlation dimension (D2)	The minimum number of variables required to construct a system dynamics model
Determinism (DET)	Recurrence plot analysis determinism
Detrended fluctuation analysis (DFA)	A nonlinear index of HRV that extracts the correlations between successive R-R intervals over different time scales and yields estimates of short-term (α1) and long-term (α2) fluctuations
End-tidal CO2 (ETCO2)	The carbon dioxide level measured at the end of exhalation
Heartfelt emotion (HFE)	Experiencing emotions of appreciation, love, care, and compassion
Heart rate (HR)	The number of heartbeats per min
High-frequency (HF) band	A HRV frequency range from 0.15 to 0.40 Hz that represents the inhibition and activation of the vagus nerve by breathing (respiratory sinus arrhythmia)
HR Max—HR Min	An HRV index that calculates the difference between the highest and lowest HRs during each respiratory cycle
Inhalation-to-exhalation (I/E) ratio	The ratio of inspiratory to expiratory time
Low-frequency (LF) band	A HRV frequency range of 0.04–0.15 Hz that may represent the influence of PNS and baroreflex activity (when breathing at the RF)
Natural logarithm (Ln)	The logarithm to the base *e* (2.71828…)
NN50	The number of adjacent NN intervals that differ from each other by more than 50 ms
Normal units (nu)	Dividing the absolute power for a specific frequency band by the summed absolute power of the LF and HF bands
Peak frequency (PkFreq)	The highest-amplitude frequency
pNN50	The percentage of adjacent NN intervals that differ from each other by more than 50 ms
Resonance frequency (RF)	The frequency at which a system, like the cardiovascular system, can be activated or stimulated
Respiration rate (RR)	The number of breaths per min (bpm)
Respiratory exchange ratio (RER)	The volume of CO2 removed from the body / volume of O2 consumed
Respiratory sinus arrhythmia (RSA)	The respiration-driven heart rhythm that contributes to the high frequency (HF) component of heart rate variability
RMSSD	The square root of the mean squared difference of adjacent NN intervals
Sample entropy (SampEn)	A nonlinear index of HRV that was designed to provide a less-biased measure of signal regularity and complexity than ApEn
SD1	Poincaré plot standard deviation perpendicular to the line of identity
SD2	Poincaré plot standard deviation along the line of identity
SDNN	The standard deviation of the normal (NN) sinus-initiated IBIs measured in ms
Skin conductance level (SCL)	A tonic measurement of changes in the skin's ability to carry an electric current measured in microsiemens
Tidal volume (TV)	The air volume moved into or out of the lungs during a normal breath
Triangular index (TI)	The integral of the density of the RR interval histogram divided by its height
Triangular interpolation of the NN interval (TINN)	The baseline width of the RR interval histogram
Very-low-frequency (VLF) band	A HRV frequency range of 0.003–0.04 Hz that may represent temperature regulation, plasma renin fluctuations, endothelial and physical activity influences, and possible intrinsic cardiac, PNS, and SNS contributions

measure breathing effort using the excursion of a respirometer (i.e., a flexible respiratory band sensor) placed over the abdomen.

The I/E ratio studies showed that exhaling twice as long as inhaling did not affect autonomic, time-, frequency-domain, or nonlinear HRV metrics. Although clinicians may prefer a 1:2 I/E ratio for its potential health benefits, it did not produce gains in autonomic or HRV measurements.

We recommend that future researchers obtain larger and more diverse samples to increase statistical power and external validity.

Adjunctive Procedures to Reinforce HRVB

The adjunctive techniques studies encompassed Autogenic and Norman Cousins relaxation exercises, Kargyyra throat-singing, singing a fundamental note, chanting “om,” ujjayi breathing, and emotional self-regulation studies.

The Cousins Relaxation Exercise Increases HRV

In this w/s RCT ($N = 15$), Bax and colleagues (2007) assigned participants to listen to one of two orders of autogenic training (AT) and the Cousins relaxation exercise (CRE) for 15 min, separated by a 3-min buffer period. We recorded 15-min Autogenic and Norman Cousins exercises. The Autogenic Relaxation exercise (Charlesworth & Nathan, 1984) encouraged heaviness and warmth sensations. The Norman Cousins relaxation exercise (Peper et al., 2002) contained guided imagery promoting cardiovascular changes (e.g., allowing blood to flow into the hands). The participants sat upright with their eyes closed while listening to each recording. The AT condition did not affect the SDNN, RR, or respiration amplitude compared with the preceding resting BL. However, the CRE condition increased respiration amplitude and the SDNN and decreased RR from the BL. This study supported assigning the CRE as a home practice exercise to enhance HRVB.

The Effects of Kargyraa Throat-Singing and Singing a Fundamental Note on HRV

In this w/s RCT ($N = 11$), Grant and colleagues (2010) assigned participants to randomized orders of performing 10 min of Kargyraa throat singing or singing a fundamental note (a, e, or u) used in throat singing or sitting quietly. Kargyraa throat singing involves simultaneously producing a fundamental note and an undertone half its frequency, creating the perception of two different pitches (Levin & Edgerton, 1999). Following training until participants could perform both techniques, they sat upright with their eyes open without feedback. HR Max-HR Min and the SDNN were greater when singing a fundamental note than sitting quietly. Throat singing only increased HR Max-HR Min compared to sitting quietly. This experiment supported assigning singing a fundamental note for home practice due to its simplicity and HRV effects.

Chanting “Om” Increases HRV by Slowing Respiration

In this w/s RCT ($N = 17$), Wally and colleagues (2011) assigned participants to randomized orders of three 10-min conditions separated by 3-min buffer periods: chanting “om,” singing the fundamental note “e,” or silence. Following training to chant “om” or sing “e,” participants sat upright with their eyes open without feedback. The RR decreased, and HR Max-HR Min and the SDNN increased when chanting “om” than sitting quietly. Slowed breathing accounted for 52% of HR Max- HR Min and 59% of the SDNN variability. Although the RR did not slow when singing “e,” HR Max-HR Min increased from sitting quietly. This study demonstrated that chanting “om” could reinforce HRVB.

Can Ujjayi Breathing Increase the Effectiveness of 6-bpm HRV Training?

In this w/s RCT ($N = 22$), Fuller and colleagues (2012a) assigned participants to randomized orders of three 5-min conditions separated by 2-min buffer periods: 6-bpm ujjayi breathing involving slightly constricting the throat and producing an audible breathing sound (Mason et al., 2013), 6-bpm PB, and sitting quietly with no breathing instructions. Following training to criterion to perform 6-bpm ujjayi and 6-bpm PB, participants sat upright with their eyes open without feedback. Respiration rate and depth were identical during the two experimental conditions. The 6-bpm ujjayi condition increased HR Max-HR Min, LF percentage power, and the controversial LF/HF ratio compared to sitting quietly. Ujjayi breathing was not superior to 6-bpm PB on any HRV metric. The 6-bpm PB condition increased the same measures and the SDNN compared to sitting quietly. This study showed that both 6-bpm ujjayi and 6-bpm PB are promising home practice exercises.

Does Heartfelt Emotion increase HRV?

In this w/s RCT ($N = 25$), Fuller and colleagues (2012b) assigned participants to one of two orders of two 5-min conditions separated by a 2-min buffer period: heartfelt emotion and sitting quietly. Participants in the heartfelt emotion (HFE) condition received the HeartMath® Institute’s Heart Lock-In Technique® instructions (McCraty, 2017). Participants sat upright with their eyes open without breathing instructions or feedback in both conditions. The Heart Lock-In Technique® successfully manipulated HFE since 5-point subjective HFE ratings and PANAS-X Positive Affect subscale scores (Watson & Clark, 1994) were higher in the HFE than in the control condition. Respiration rates were identical in both conditions. HFE did not significantly increase HRV as measured by time-domain (HR Max—HR Min, NN50, pNN50, RMSSD, SDNN), frequency-domain, domain (VLF, LF, HF, LF/HF power, and peak LF frequency power), or nonlinear (approximate entropy and sample entropy) indices compared to the control condition. This study found no evidence that HFE increased HRV.

Does Adding Heartfelt Emotion to Resonance Frequency Breathing Increase HRV?

In this w/s RCT ($N=26$), Fuller and colleagues (2012c) assigned participants trained to breathe at their resonance frequency (RF) to randomized orders of three 5-min conditions separated by 2-min buffer periods: RF breathing, RF breathing with HFE, and sitting quietly. Participants sat upright with their eyes open without breathing instructions or feedback. The researchers instructed them to follow an animated pacer set at their resonance frequency, and they received HRVB in the two RF conditions. In the RF breathing with HFE condition, participants also received the HeartMath® Institute's Heart Lock-In Technique® instructions (McCraty, 2017). The Heart Lock-In Technique® successfully manipulated HFE since 5-point HFE, and PANAS-X Positive Affect subscale scores (Watson & Clark, 1994) were higher in the RF breathing with HFE condition than in the RF breathing or control conditions. Respiration rates were identical during both RF breathing conditions. Although both RF breathing conditions produced greater HR Max—HR Min, pNN50, RMSSD, and SDNN measurements than the control condition, in no case did adding HFE instructions to RF breathing produce greater HRV values than RF breathing alone. This experiment further questioned HFE's potential contribution to HRVB.

Can Heartfelt Emotion Facilitate Autonomic Recovery from a Math Stressor?

In this w/s RCT ($N=24$), Korenfeld and colleagues (2013a) assigned participants to one of two sequences of 5-min conditions separated by 5-min buffer periods. Half of the participants started with the serial sevens-HFE sequence and half with the serial sevens-control sequence. There was a 5-min buffer period between each sequence during which participants sat quietly. Participants sat upright with their eyes open in all conditions without breathing instructions or feedback. In the HFE condition, participants utilized the HeartMath® Institute's Heart Lock-In Technique® instructions (McCraty, 2017) which they had practiced for 15 min per day for at least 2 weeks. In the control condition, participants sat quietly. After the HFE or control condition, participants performed a 5-min videotaped serial sevens task in which they reported their calculations out loud. HFE and PANAS-X Positive Affect subscale scores (Watson & Clark, 1994) were higher in the HFE condition than in the control condition. HFE following a serial sevens stressor did not aid recovery more than the control condition for autonomic (BP, HR, SCL, TEMP), HRV time-domain (HR Max-HR Min, NN50, pNN50, RMSSD, SDNN), or frequency-domain (VLF, LF, HF, LF/HF) metrics. "Immunization" with HFE did not facilitate recovery following exposure to a math stressor.

Can Heartfelt Emotion Attenuate the Autonomic Effects of a Math Stressor?

In this w/s RCT ($N=24$), Korenfeld and colleagues (2013b) randomly assigned participants to two sequences of 5-min conditions separated by 5-min buffer periods. Half of the participants started with the serial sevens-HFE sequence and half with the serial sevens-control sequence. We videotaped participants as they reported their calculations out loud in the serial sevens condition. There was a 5-min buffer period between each sequence during which participants sat quietly. Participants sat upright with their eyes open in all conditions without breathing instructions or physiological feedback. In the HFE condition, participants utilized the HeartMath® Institute's Heart Lock-In Technique® instructions, which they had practiced for 15 min per day for at least 2 weeks. In the control condition, participants sat quietly. HFE and PANAS-X Positive Affect subscale scores (Watson & Clark, 1994) were higher in the HFE condition than in the control condition. HFE following a serial sevens stressor did not aid recovery more than the control condition for autonomic (BP, HR, SCL, TEMP), HRV time-domain (HR Max-HR Min, NN50, pNN50, RMSSD, SDNN), or frequency-domain (VLF, LF, HF, LF/HF) measurements. HFE did not facilitate recovery following a math stressor.

Adjunctive Studies Summary

These studies provided evidence that the CRE, singing a fundamental note, chanting "om," 6-bpm ujjayi breathing, and 6-bpm PB are promising home exercises to increase HRV. Activating HFE using HeartMath® Institute's Heart Lock-In Technique® did not increase HRV, enhance the effects of RF breathing, "immunize" participants against a math stressor, or aid their recovery following a math stressor.

We recommend that future researchers obtain larger and more diverse samples. We encourage investigators to study alternative methods to activate and measure HFE and advise at least 2 weeks of practice to ensure skill acquisition.

HRVB Training Studies

The HRVB training studies examined RF test–retest reliability and the effects of HRVB on SCL and TEMP.

Resonance Frequency Measurements are Reliable

In this w/s study ($N = 19$), Fuller and colleagues (2011) evaluated the 2-week test–retest reliability of the RF, HR Max-HR Min, pNN50, and SDNN. Participants sat upright in a chair with eyes open throughout this study. Following 10-min stabilization and a 5-min resting BL, the experimenters measured their RF using a procedure informed by Lehrer and colleagues (2000). The investigators instructed participants to follow an animated pacing display designed to guide their breathing from 7.5 to 4.5 bpm in seven descending ½-bpm steps. They breathed at each target rate for 5 min, followed by a 1-min buffer period. The researchers confirmed the successful completion of each step before moving to the next. They determined the RF using six criteria (HR-respiration phase synchrony, RSA, low-frequency power, and largest RMSSD, SDNN, and pNN50 values). The RF was the rate that maximized the most criteria, with the greatest weight assigned to phase synchrony, RSA, and low-frequency power. They retested the participants using the same procedure 2 weeks later to assess the reliability of these measurements. The participants received no HRV training or breathing practice during this period. Although RF ($r = 0.73$), pNN50 ($r = 0.65$), and the SDNN ($r = 0.59$) measurements were reliable, HR Max-HR Min was not. This study showed that the RF was stable over 2 weeks.

HRVB Training Raises Temperature and Lowers Skin Conductance

In this mixed-design RCT ($N = 21$), Zerr et al. (2014) pre-assessed participants using the State-Trait Anxiety Inventory (Spielberger, 1983), matched them on State Anxiety scores, and then randomly assigned them to four sessions of either HRV or temperature biofeedback. Each weekly training session consisted of stabilization (5 min), pre-BL (5 min), biofeedback training (30 min), and post-BL (5 min) conditions. The experimenters instructed the HRVB group to sit upright, breathe six times per min, and increase peak-to-trough HR differences. They received visual analog respirometer and HRV feedback and practiced breathing six times per min for 15 min a day. The researchers instructed the TEMP biofeedback group to sit upright and increase dorsal index finger temperature. They received visual analog temperature feedback and practiced hand-warming for 15 min a day. Weekly logs confirmed compliance. The HRVB group increased the SDNN (69.3–93.8 ms) and temperature (90.2–94.3 °F) and decreased SCL (5.8–2.3 µS) from session 1 pre-BL to session 4 post-BL. Although the TEMP group also increased TEMP (88.8–92.2 °F) from session 1 to session 4, they did not improve on SDNN or SCL. The HRVB group's session 4 temperature was higher, correcting for pre-BL differences.

This study demonstrated that HRVB could precede and replace dedicated temperature and SCL biofeedback for clients who achieve normal values (e.g., temperature ≥ 95 °F and SCL < 5 µS/cm^2).

HRVB Training Study Summary

The RF reliability study showed that our RF measurement protocol could achieve acceptable 2-week test–retest reliability in undergraduates. This finding was critical since RF HRVB protocols assume that the RF is stable cardiovascular system property in adults that is determined by the volume of blood in the vascular tree. If RF measurements were unstable, clinicians might use 6-bpm PB instead.

This experiment revealed that RF measurement is not always straightforward. In our small data set ($N = 19$), a single breathing rate never maximized all six of the weighted criteria. Moreover, no single criterion reliably identified the participants' RF.

The comparison of 4 weeks of HRVB and TEMP training demonstrated that only HRVB increased the SDNN and that HRVB may produce greater index finger temperature increases than dedicated TEMP biofeedback. If these findings are replicated, they would support starting autonomic training with HRVB before initiating TEMP or SCL biofeedback.

Future researchers should replicate these findings with larger and more diverse samples. Since individuals may not consistently breathe at the target rates (e.g., 5.75 instead of 5.5 bpm) during RF trials, investigators should consider using 0.25-bpm steps to increase test–retest reliability. Also, they could follow the initial RF assessment with a fine-tuning trial (Lehrer et al., 2013). For example, researchers could ask participants to breathe three 0.25-bpm steps above and below the RF to mitigate the effects of measurement error.

To compare HRVB with TEMP training, researchers should match participants on hand temperature to ensure group equivalence on this variable. They might add a SCL training group to compare the effects of all three modalities on HRV, SCL, and temperature. In addition, they could investigate the optimal training time for these modalities. Do 30-min training sessions produce greater physiological change than 20-min sessions?

The Concurrent Validity of Ultra-Short-Term (UST) HRV Measurements

Researchers have attempted to estimate *short-term* (ST; ~ 5 min) HRV using briefer *ultra-short-term* (UST; < 5 min) measurements (Shaffer et al., 2020). The UST studies investigated whether artifacted resting UST values can achieve strong concurrent validity for HRV time-domain, frequency-domain, and nonlinear measurements compared to 5-min resting BL values. *Concurrent validity* is the degree to which values obtained from proposed and established measurement procedures are correlated.

Ultra-Short-Term (UST) HRV Measurements can Achieve Strong Concurrent Validity

In a w/s RCT ($N = 38$), Shearman and colleagues (2018) stabilized participants for 5 min and then monitored them for 7 min sitting upright, with eyes open, no feedback, and instructions to breathe normally. The investigators extracted 10-, 20-, 30-, 60-, 90-, 120-, 180-, and 240-s segments from 5-min resting ECG recordings. The researchers measured concurrent validity between the UST and 5-min measurements using a Pearson Product-Moment Correlation Coefficient. They selected a conservative criterion ($r = 0.90$) because the calculation of UST and 5-min measurements from the same data set should be expected to inflate correlation values. This cut-off ensured that UST values would account for at least 81% of the variability in 5-min values. Resting UST epochs of differing lengths achieved strong concurrent validity for HR, time-domain (NN50, pNN50, RMSSD, SDNN), frequency-domain (HF nu, HF power, LF nu, LF power, the LF/HF ratio), and nonlinear metrics (DFA α1, DFA α2, DET, SampEn, SD1, SD2, ShanEn). D2 did not achieve acceptable concurrent validity. Resting BLs as brief as 1 min estimated 5-min HR, SDNN, and RMSSD for the undergraduate participants.

Limits of Agreement Determination of Minimum Epochs for Estimating 5-Minute UST-HRV Measurements

In a w/s RCT ($N = 85$), Urban and colleagues (2019a) stabilized participants for 5 min and then monitored for 7 min sitting upright, with eyes open, no feedback, and instructions to breathe normally. The investigators extracted 10-, 20-, 30-, 60-, 90-, 120-, 180-, and 240-s segments from 5-min resting ECG recordings. For each of 28 HRV metrics, investigators compared each segment length (10 s through 240 s) with its corresponding 5-min value using a Pearson correlation coefficient ($r \geq 0.90$) and the Bland–Altman Limits of Agreement (LoA) technique (allowable difference within ± 10% of a 5-min value's range) at Richard Gevirtz's suggestion. For 23 of 28 metrics, the Pearson r was more rigorous than the LoA criterion. For 2 metrics, the LoA criterion was more rigorous; for 2 metrics, both criteria were equally rigorous. Neither criterion achieved acceptable concurrent validity for ApEn. As in the previous study, resting BLs as brief as 1 min estimated 5-min HR, SDNN, and RMSSD for the undergraduate participants.

Concurrent Validity Study Summary

"UST measurements are proxies of proxies. They seek to replace short-term values which, in turn, attempt to estimate long-term metrics" (Shaffer et al., 2020). The first concurrent validity study demonstrated that epochs of varying lengths were required to estimate 5-min time-domain, frequency-domain, and nonlinear HRV metrics using a Pearson criterion of $r \geq 0.90$. Although 1-min epochs estimated 5-min HR, SDNN, and RMSSD measurements, no UST measurement estimated D2. These findings have implications for consumer-grade HRV applications that calculate RMSSD using shorter periods of unartifacted data.

Fleming and DeMets (1996) cautioned that "A correlate does not a surrogate make" (p. 605). The second study examined the concurrent validity of UST measurements using Pearson r and LOA criteria. Correlation does not ensure measurement precision. The LOA requirement imposed an allowable difference (± 10% of a 5-min value's range). Although the Pearson criterion was more rigorous for 23 of 28 metrics, the LOA criterion was more stringent for 2 variables.

We encourage future researchers to replicate these findings with larger and more diverse samples and apply both Pearson and LOA criteria to artifacted and normalized data.

Rhythmical Skeletal Muscle Tension (RSMT) Strategies to Increase HRV

The late Evgeny Vaschillo's (2018) AAPB Distinguished Scientist address inspired two RSMT studies that replicated Dr. Vaschillo and colleagues' (2011) findings and compared the effects of different RSMT frequencies.

Confirmation that RSMT Can Increase Heart Rate Variability

In this w/s RCT ($N = 40$), Urban and colleagues (2019b) randomly assigned participants to one of six orders of 5-min trials of 3, 6, and 12 muscle contractions per min (cpm), separated by 3-min buffer periods. Participants received verbal prompts to perform simultaneous hand and foot contractions for 3 s but did not receive feedback. The investigators visually confirmed compliance with wrist-and-ankle-contraction instructions. The participants contracted their hands and feet at the prescribed frequencies. The respiration rate was constant across all RSMT conditions. The 6-cpm condition produced a mean PkFreq of ~ 0.1 Hz compared with 0.09 at 3 cpm and 0.11 at 12 cpm. RMST at 6 cpm produced greater Ln LF power, Ln RMSSD, LnSD1, LnSD2, and LnSDNN compared to 12 cpm. There was no difference between 3 and 6 cpm on these measures, suggesting that these rates activated different resonances. These findings demonstrated that 6-cpm RSMT could provide clients with an alternative exercise for increasing HRV.

RSMT Increases HRV at 1- and 6 Contractions per Minute

In this w/s RCT ($N=49$), Shaffer and colleagues (2022) randomly assigned participants to one of six orders of 5-min trials of 1, 6, and 12 muscle contractions per min (cpm), separated by 3-min buffer periods. Participants received verbal prompts to perform simultaneous hand and foot contractions for 3 s but did not receive feedback. The investigators visually confirmed compliance with wrist-and-ankle-contraction instructions. The participants contracted their hands and feet at the prescribed frequencies. The RRs exceeded the RF range within 1 bpm across the three RSMT conditions. RMST at 6 cpm yielded a PkFreq of ~ 0.10 Hz. RSMT at 1 and 6 cpm increased five time-domain metrics (HR Max—HR Min, RMSSD, SDNN, TI, and TINN), one frequency-domain metric (LF power), and three nonlinear metrics (D2, SD1, SD2) more than RSMT at 12 cpm. The 1-cpm rate (~ 0.02 Hz) may have stimulated the hypothesized VT baroreflex between 0.02 and 0.055 Hz, while the 6-cpm rate (0.1 Hz) may have stimulated a hypothesized HR baroreflex between 0.055 and 0.11 (see Vaschillo et al., 2002). RSMT may help patients who suffer from phrenic nerve damage, eliminating the RSA. This technique may assist patients who find slow-PB difficult (e.g., anxiety disorders and chronic pain). RSMT may help patients who should not breathe at the RF range because their faster breathing rates compensate for an abnormal acid–base balance. Finally, this study showed that patients could generate comparable RSA increases by performing RSMT at 1 or 6 cpm.

RSMT Study Summary

A series of two studies replicated Vaschillo and colleagues' (2011) discovery that RMST can increase HRV, independent of breathing rate. We did not anticipate that 1-, 3-, and 6-cpm RSMT would produce comparable HRV increases. The disassembly study reported in this section showed that 6-cpm wrist-and-ankle RSMT produced greater HRV increases than 6-cpm wrist or ankle contraction alone.

Future researchers should replicate these findings with a more diverse sample and explore the mechanisms mediating these effects. In addition, we encourage them to investigate whether 6-cpm wrist-core muscle-and-ankle RSMT can produce greater resonance effects than wrist-and-ankle RSMT.

Recommendations for Future Development of Our Work

We encourage future researchers to replicate our findings with larger, more diverse (e.g., age and health) samples balanced for gender for greater statistical power and external validity.

In addition to the questions we raised in our study summaries, our five arcs of HRV research have identified important questions with practical significance for HRVB training:

(1). What minimum trial lengths are necessary to determine the RF?
(2). Would descending 0.25-bpm trials increase the test–retest reliability of RF assessment compared to 0.5-bpm trials?
(3). Is a "sliding" RF assessment protocol based on actual breathing frequencies (Fisher & Lehrer, 2022) more accurate than a "stepped" method that requires clients to follow a breathing pacer for several minutes?
(4). How critical is training at the RF? Is RF training superior to 6-bpm PB for all validated HRV applications? At what distance from the RF (e.g., ± 0.5 bpm) do PB training outcomes significantly decline?
(5). Is there an optimal HRVB session length? Does this duration differ by client characteristics (e.g., age, presenting problem) or training goal (e.g., clinical or performance)?
(6). How many HRVB training sessions are required for most clients to achieve stable clinical or performance gains? Which HRV changes are most strongly associated with improvement? How many weeks do these changes lag behind clinical responses or better performance?
(7). Does effective HRVB training require respiratory biofeedback if we guide clients with a pacing display? Does adding respiratory feedback increase the effectiveness of RSA feedback?
(8). Does the means of stimulating the RF affect clinical and performance outcomes? Can RSMT produce the same results as PB?
(9). Does HRVB training produce greater and faster skill acquisition than following a pacing display?
(10). What is the actual compliance rate with home training assignments? Is there a minimum level of compliance required for successful HRVB training? Which are the best strategies for increasing compliance?
(11). Which are the most effective home practice assignments?

This decade represents a pivotal opportunity for HRV and HRVB, which are not yet part of mainstream medical practice. For example, nurses do not routinely monitor HRV as a vital sign during office visits, and its diagnostic use has been mainly in cardiology and obstetrics (Shaffer et al., 2020). However, in the consumer space, wearables may serve as a Trojan Horse by integrating HRV into fitness and health applications and educating the public—and medical professionals—about its importance to health and performance.

The growing number of educational resources and training applications to teach consumers compassion, emotional self-regulation, healthy breathing, HRV, and mindfulness is exciting. We encourage advocacy of rigorous scientific standards in product development and outcome research (e.g., *Evidence-Based Practice in Biofeedback and Neurofeedback,* Khazan et al., in press) to protect the integrity of this modality. Finally, we must educate professionals and the public about what HRV means, its role in health and performance, and effective strategies to increase it.

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Declarations

Conflict of interest No authors have conflict of interest to report.

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