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Resonant Breathwork as Multimodal Vagal–Interoceptive Modulation: An Empirical Synthesis of Non-invasive VNS, Breathing-Driven Interoception and Respiratory Tools

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ABSTRACT: Resonant Breathwork is proposed as a layered, measurable intervention that modulates vagal activity and interoceptive processing through acoustic vocalization, respiratory mechanics, and biofeedback. This review synthesizes human empirical studies from 2022–2025 across five domains: (1) noninvasive transcutaneous auricular vagus nerve stimulation and acoustic or vocal vagal engagement; (2) interoception targets modulated by breathing; (3) respiratory rehabilitation tools, including oscillatory positive expiratory pressure and inspiratory muscle training; (4) virtual or augmented reality breath biofeedback; and (5) neuroimaging of high ventilation breathwork with music. Evidence shows taVNS can acutely increase vagal indices, with effects contingent on frequency and pulse width, while paced humming or singing near 0.1 Hz enhances respiratory sinus arrhythmia and positive affect. Breathing phase shapes perception and neural excitability; exhalation weighting and slow pacing amplify heartbeat evoked potentials and attention to internal signals. OPEP improves airway clearance and symptoms, and inspiratory training increases inspiratory strength with shifts toward parasympathetic balance, suggesting autonomic co benefits beyond pulmonary gains. XR delivery yields physiologic outcomes comparable to non XR biofeedback but improves engagement and transfer in stress laden contexts. Neuroimaging during high ventilation plus music reveals reduced perfusion in interoceptive cortex and increased perfusion in limbic regions alongside sympathetic activation and post session emotional relief. Findings align with a testable framework in which acoustic resonance, mechanical load, and feedback guided timing jointly modulate vagal efference and interoceptive circuitry, with translational potential for neurodivergent and post viral dysautonomia.

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KEYWORDS:
Resonant breathwork, Transcutaneous auricular vagus nerve stimulation, Interoception, Heart rate variability, Oscillatory positive expiratory pressure

I. INTRODUCTION

Resonant Breathwork denotes a three-layer construct that integrates (a) vocal–acoustic vagal engagement through humming, toning, or paced singing; (b) mechanical oscillation and resistance via oscillatory positive expiratory pressure and inspiratory loading; and (c) biofeedback-supported pacing that stabilizes respiratory rhythm and cardiorespiratory coupling. Acoustic engagement near the resonance frequency (~0.1 Hz) yields respiratory sinus arrhythmia amplification comparable to paced breathing, indicating a practicable route to vagal modulation through voice production and sound-mediated exhalation control (Tanzmeister et al., 2022). Mechanical aids, including OPEP devices and inspiratory muscle training, provide quantifiable gains in airway clearance, perceived breathlessness, and inspiratory strength, with emerging evidence of autonomic co-benefits reflected in heart-rate variability shifts (Alghamdi et al., 2023; Sa-nguanmoo et al., 2025). Biofeedback-supported pacing delivered through immersive or conventional interfaces standardizes rate and depth while scaffolding adherence, although randomized evidence suggests physiological efficacy that matches non-VR comparators rather than surpasses them (Cortez-Vázquez et al., 2024). Clinical relevance is pronounced for neurodivergent and post-viral cohorts characterized by dysautonomia, breath irregularity, and interoceptive disruption, where inspiratory training and structured respiratory practice have demonstrated improvements in breathlessness domains and functional indices (McNarry et al., 2022). Convergent neuromodulation studies additionally indicate that transcutaneous auricular vagus nerve stimulation (taVNS) can acutely increase parasympathetic indices—particularly high-frequency HRV—with age and parameter settings moderating effect size (Gianlorenço et al., 2024; Maestri et al., 2024). Yet parameter-sensitivity trials reveal heterogeneous HRV responses across frequency–pulse-width combinations, underscoring the need for protocol optimization (Atanackov et al., 2025). At the upper arousal boundary of breath-based practices, high-ventilation breathwork combined with music produces altered states marked by decreased HRV during induction and regionally specific perfusion shifts on ASL-MRI—findings that complement slower resonance regimens within a unified continuum of autonomic and affective modulation (Kartar et al., 2025).

Despite these advances, the evidentiary landscape remains fragmented across taVNS trials, vocal pacing studies, respiratory devices, and XR biofeedback systems, which hinders cumulative theory-building and parameterized protocol design. The present article addresses this gap by delimiting its scope to human empirical work from 2022–2025 that reports physiological endpoints capable of indexing autonomic and interoceptive change: HRV (e.g., RMSSD, HF), respiration metrics (rate, variability, end-tidal CO_2), spirometry and respiratory muscle strength, EEG heartbeat-evoked potentials (HEP), and ASL-MRI or fMRI perfusion. Five focus domains structure the synthesis: (1) non-invasive VNS and acoustic/vocal vagal engagement; (2) interoceptive targets modulated by breathing; (3) respiratory rehabilitation tools with measurable physiology; (4) VR/AR and HCI breath biofeedback; and (5) neuroimaging of high-ventilation breathwork with music. Mechanistic interoception findings constrain timing choices: exhalation phases enhance HEP amplitude during heartbeat attention, and respiratory phase two seconds before action predicts response speed and accuracy, implying design leverage for exhale-weighted cues and ~0.1 Hz pacing (Zaccaro et al., 2024; Harting et al., 2025). Respiratory tools provide robust pulmonary endpoints and, where assessed, shifts in sympathovagal balance that align with reduced effort and improved regulation (Alghamdi et al., 2023; Sa-nguanmoo et al., 2025). Meta-analytic evidence indicates that VR breathing interventions are not intrinsically superior to non-VR breathing on mental health, HR, or HRV outcomes, but immersive delivery may still augment adherence and skill transfer in stressful contexts of use (Cortez-Vázquez et al., 2024). Altogether, these streams motivate an integrating framework that links acoustic resonance, mechanical loading, and feedback-guided pacing to reproducible autonomic and interoceptive signatures.

The central hypothesis advanced here posits that layered acoustic–mechanical–feedback inputs shift vagal indices and interoceptive metrics in predictable, parameter-dependent ways that can be engineered through selection of frequency, pulse width, montage, pacing rate, and exhale/inhale weighting. Methodologically, the review follows PRISMA-aligned identification, screening, and extraction, with risk-of-bias appraisal and transparent effect-direction synthesis across heterogeneous endpoints (Page et al., 2021). Parameter-sensitivity mapping is undertaken for taVNS (frequency, pulse width, laterality) and for vocal/paced breathing near resonance, with attention to respiration control during HRV acquisition and to montage-specific afferent engagement. The analysis cross-walks measurement families—time- and frequency-domain HRV, respiration metrics and capnography, spirometry and MIP/MEP, EEG HEP, and ASL-MRI—to the three layers of Resonant Breathwork to inform dose, sequence, and safety monitoring. Evidence prioritized includes randomized or crossover taVNS trials with autonomic readouts, mechanistic singing/humming protocols, controlled studies of OPEP and IMT, XR biofeedback trials or meta-analyses, and the recent ASL-MRI breathwork–music investigation (Gianlorenço et al., 2024; Maestri et al., 2024; Atanackov et al., 2025; Tanzmeister et al., 2022; Alghamdi et al., 2023; Sa-nguanmoo et al., 2025; Cortez-Vázquez et al., 2024; Kartar et al., 2025). Intended contributions include a parameterized protocol template, a metrics-to-design map aligned with study objectives, and translational recommendations for neurodivergent and post-viral use-cases where dysautonomia and interoceptive dysregulation are salient constraints. By integrating acoustic, mechanical, and feedback layers under a common measurement architecture, the article furnishes a testable model for layered breath–vagus interventions and a roadmap for next-generation controlled trials **(Figure 1)**.

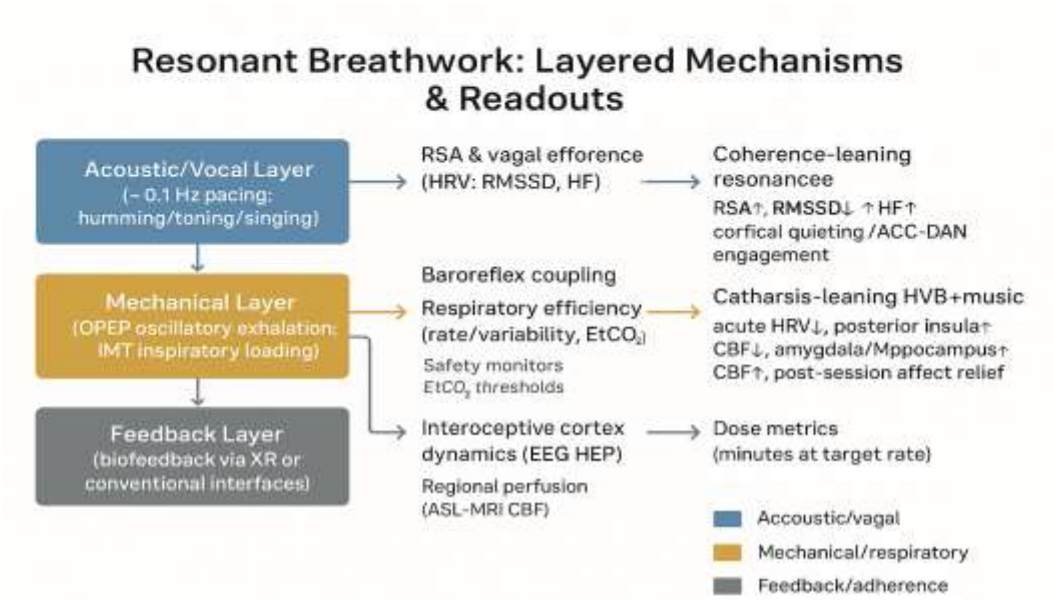

Figure 1. Conceptual Systems Diagram of Resonant Breathwork

II. LITERATURE REVIEW

A) Non-invasive VNS and acoustics. Recent randomized and crossover trials indicate that taVNS can acutely modulate autonomic indices, with heterogeneity driven by stimulation parameters and sample characteristics. In a sham-controlled RCT, taVNS increased high-frequency HRV (HF) relative to sham, with age moderating the effect such that older adults exhibited larger HF gains—consistent with greater headroom for parasympathetic up-regulation (Gianlorenço et al., 2024). Parameter-sensitivity work using a within-subject crossover design demonstrated that specific frequency–pulse-width pairs (e.g., 10 Hz×250–500 µs; 25 Hz×100 µs) can raise overall variability (SDNN) without reliably changing RMSSD, underscoring a distinction between global variability and vagally mediated indices (Atanackov et al., 2025). Converging evidence from a double-blind, sham-controlled exercise study shows that one week of daily taVNS increased VO_2peak (~3–4%) and peak work rate while attenuating inflammatory responses, suggesting cardiorespiratory and immunomodulatory benefits beyond resting HRV (Ackland et al., 2025). Not all trials show vagal enhancement: a crossover study reported decreases in RMSSD and HF during taVNS without heart-rate change, implying context- or parameter-dependent arousal effects of vagal afferent activation (Kaduk et al., 2025). Montage also matters; post hoc comparisons favor in-ear (tragus/concha) placements over behind-ear sites for RMSSD increases, aligning with auricular vagal innervation density (Percin et al., 2024). Complementing electrical stimulation, acoustic/vocal protocols near the cardiorespiratory resonance frequency (~0.1 Hz) produce robust RSA: paced singing at 0.1 Hz matched slow-breathing benefits on HRV, with added positive affect (Tanzmeister et al., 2022), and brief humming or OM chanting elevated HRV time- and frequency-domain markers in field and lab assessments (Trivedi et al., 2023; Inbaraj et al., 2022). Taken together, these findings position acoustic pre-activation (humming/toning) as a low-barrier entry to vagal engagement and integration-phase vocalization (paced singing) as a means to sustain resonance within the Resonant Breathwork sequence.

B) Interoception modulated by breathing. A growing body of evidence clarifies how respiration phase and breath-focused attention shape perception and brain dynamics, with direct implications for cue timing in protocols. A large multi-dataset analysis showed that respiratory phase ~2 s before response predicts reaction-time and accuracy fluctuations across tasks, implying a systematic, time-lagged coupling between breathing and sensorimotor readiness (Harting et al., 2025). EEG work demonstrates that exhalation preferentially amplifies the HEP and improves heartbeat detection accuracy during interoceptive attention, supporting exhale-weighted tasking when training interoceptive precision (Zaccaro et al., 2024). Breath-focused fMRI paradigms reveal a characteristic neural signature: widespread cortical deactivation with preserved or strengthened ACC–dorsal attention connectivity during breath awareness, particularly in individuals with higher interoceptive sensibility (Farb et al., 2023). These laboratory observations cohere with reports that volitional slow breathing entrains delta–theta oscillations and modulates limbic–insular networks, offering a mechanistic substrate for the attentional quieting and enhanced bodily signal gain targeted by resonance-paced practice (contextualized in the sources above). Distinguishing interoceptive accuracy (objective performance) from interoceptive awareness (subjective sensibility) is therefore critical; phase-specific protocols can be structured to favor accuracy gains (e.g., exhale-locked heartbeat tasks) while breath-awareness blocks can consolidate attentional stability reflected in large-scale network dynamics. Collectively, these studies argue for slow pacing (~0.1 Hz) with exhale-emphasis during interoceptive drills inside Resonant Breathwork, so that cueing aligns with phases of maximal cortical receptivity to internal signals (Zaccaro et al., 2024; Harting et al., 2025).

C) Respiratory rehabilitation tools. Controlled trials since 2022 support oscillatory positive expiratory pressure (OPEP) and inspiratory muscle training (IMT) as mechanical levers with measurable physiology that may carry autonomic co-benefits. In the O-COPD randomized trial (n = 122), three months of Acapella OPEP improved cough-specific quality of life, reduced 24-h cough counts, and enhanced fatigue and generic health indices versus usual care, consistent with clinically meaningful airway-clearance gains (Alghamdi et al., 2023). In bronchiectasis, a 6-month single-arm pilot reported fewer exacerbations and improved Bronchiectasis Health Questionnaire scores with twice-daily Flutter use, alongside transient increases in sputum volume—an expected marker of mobilization (Kim et al., 2023). Regarding autonomic outcomes, a 4-week RCT in obese young adults found that IMT (55% MIP) increased inspiratory strength and shifted sympathovagal balance (LF/HF ↓) without altering spirometric volumes, suggesting an HRV benefit attributable to respiratory-muscle loading rather than parenchymal change (Sa-nguanmoo et al., 2025). For post-viral recovery, an RCT in long-COVID showed home-based IMT improved breathlessness and respiratory-muscle function—a clinical platform on which autonomic indices can be layered in future trials (McNarry et al., 2022). While HRV endpoints are not yet routine in airway-clearance trials, the prolonged, resistive exhalation intrinsic to OPEP and the baroreflex-salient inspiratory loading of IMT plausibly foster RSA and vagal rebound when embedded within resonance-paced sessions, aligning these devices with the mechanical layer of Resonant Breathwork.

D) VR/AR and HCI breath biofeedback. The current RCT evidence indicates that **immersive delivery** does not intrinsically outperform non-immersive delivery on physiologic regulation, even as it may enhance adherence or skill generalization in high-arousal contexts. A 2024 systematic review and meta-analysis of six RCTs found no significant differences between VR and non-VR breathing interventions on mental-health outcomes, heart rate, or HRV, nor in user likeability or intended future use (Cortez-Vázquez et al., 2024). At the same time, single-case and training studies suggest that closed-loop biofeedback inside ecologically valid VR scenarios can strengthen voluntary HRV control and breathing regularity under stress—an effect profile valuable for transfer, even if session-level physiology matches non-VR practice (Michela et al., 2022; Michela, 2024). Broader rehabilitation reports integrating VR with pulmonary protocols in post-COVID populations show feasibility and functional gains, though they rarely isolate breath-biofeedback's unique contribution to HRV endpoints (Rutkowski et al., 2023). The resulting picture is one of parity in acute physiological effects but potential advantages in engagement, dosage, and context-specific skill acquisition, positioning XR as a delivery amplifier for the biofeedback-supported pacing layer rather than a categorical efficacy upgrade over conventional tools (Cortez-Vázquez et al., 2024; Michela et al., 2022).

E) Breathwork plus music neuroimaging. High-ventilation breathwork (HVB) accompanied by evocative music evokes altered-state phenomenology with a distinctive autonomic–neural signature that complements slower resonance practices. In a multimodal study spanning online, lab, and MRI cohorts, ASL-MRI during sustained HVB revealed reduced perfusion in left posterior insula/parietal operculum (interoceptive/self regions) and increased perfusion in right amygdala–anterior hippocampus (emotion–memory), with regional changes tracking "oceanic boundlessness" (unity/bliss) ratings; concurrently, HRV decreased during induction, denoting sympathetic activation (Kartar et al., 2025). Press summaries from institutional and science outlets converge on this pattern—global CBF reductions with focal limbic increases, reduced fear/negative affect after sessions, and no adverse events—underscoring a "hormetic" stress narrative consistent with cathartic emotional processing (Neuroscience News, 2025; University of Sussex/BSMS, 2025). Conceptually, these findings extend the integration phase of Resonant Breathwork: while resonance-paced vocalization aims for vagal/RSA coherence and attentional quieting, HVB-plus-music transiently upshifts arousal to access limbic circuits, with post-session relief and positive affect suggesting complementary mechanisms along a single respiratory-neural continuum. Methodologically, the HVB study anchors metric selection for altered-state variants (ASL-MRI CBF maps + HRV trajectories) while the slow-breathing literature anchors RSA and interoceptive readouts—together furnishing an empirically grounded palette of outcomes for layered, parameterized breath protocols (Kartar et al., 2025; Tanzmeister et al., 2022).

III. METHODOLOGY

The review adopted a priori eligibility criteria that confined inclusion to human empirical studies published between January 1, 2022 and September 17, 2025, each reporting at least one physiological endpoint pertinent to autonomic, respiratory, or interoceptive function: HRV (RMSSD, HF power, LF/HF, RSA), respiration metrics (rate, variability, end-tidal CO_2), spirometry (FEV_1, FVC), respiratory muscle strength (MIP/MEP), EEG heartbeat-evoked potentials (HEP), and ASL-MRI cerebral blood flow (CBF). Targeted populations included neurotypical adults, neurodivergent cohorts, and post-viral groups (e.g., long COVID), with healthy-adult mechanistic experiments eligible when they clarified pathways or parameters. Study designs encompassed randomized and crossover trials, controlled cohorts, preregistered pilots, and peer-reviewed systems/engineering papers with human data, while excluding single-case reports without physiology, opinion pieces, and unblinded program evaluations lacking objective endpoints. Information sources comprised PubMed/PMC, JAMA Network, Wiley Online Library, PLOS, eLife, SpringerLink, ScienceDirect, bioRxiv/medRxiv (for preregistered pilots), and ClinicalTrials.gov (for ongoing trials and protocol parameters), with the search and reporting framework aligned to PRISMA 2020 (Page et al., 2021). Search strings combined domain terms (e.g., "taVNS RMSSD," "humming 0.1 Hz HRV," "OPEP Flutter FEV1," "IMT MIP LF/HF," "VR breathing HRV," "ASL-MRI breathwork CBF") with date limits and human filters; forward–backward citation chasing complemented database queries. Because HRV is sensitive to respiration, inclusion favored studies that either controlled breathing or reported respiratory rate/$EtCO_2$ during HRV acquisition, consistent with recent guidance on heart-rate and respiratory reporting (Quigley et al., 2024; Damoun et al., 2024). For ASL-MRI outcomes, data abstraction followed contemporary consensus on acquisition and reporting (Lindner et al., 2023; Suzuki et al., 2024), recognizing the continued relevance of the ISMRM/ESMRMB white paper (Alsop et al., 2015). A protocol and codebook enumerating eligibility decisions, variable definitions, and planned analyses were maintained to support transparent replication under PRISMA 2020 conventions (Page et al., 2021).

Screening proceeded via dual-reviewer title/abstract checks followed by full-text confirmation, with disagreements resolved by consensus and recorded in a PRISMA flow diagram (Page et al., 2021). Data extraction captured bibliographic details; population (diagnosis, age, sex), sampling and setting; intervention parameters—for taVNS: frequency (Hz), pulse width (μs), duty cycle/on–off scheduling, laterality/montage (tragus, cymba conchae, earlobe control), session length and dose; for acoustic/vocal protocols: pacing rate (breaths/min), exhale-to-inhale ratio, phonation type (humming, OM, singing); for OPEP/IMT: device model, resistance/pressure targets, session frequency/duration; for XR biofeedback: device class, biofeedback targets, task context; and for ASL-MRI: labeling scheme, PLD, readout, background suppression, CBF quantification model. Comparators (sham, wait-list, usual care, non-VR analogues) and endpoints (HRV domains, respiratory metrics, spirometry, MIP/MEP, EEG HEP, ASL-CBF), plus adherence and usability indicators (session counts, completion rates, adverse events, user ratings), were systematically recorded. Risk of bias was appraised using RoB 2 for randomized trials (Sterne et al., 2019), ROBINS-I for non-randomized studies (Sterne et al., 2016), and QUADAS-2 when diagnostic/accuracy paradigms were relevant (Whiting et al., 2011). To enhance interpretability across heterogeneous autonomic outcomes, extraction also noted whether breathing was paced or spontaneous, whether $EtCO_2$ was monitored, and whether HRV was computed over stable epochs—choices supported by contemporary reporting recommendations

(Quigley et al., 2024; Damoun et al., 2024). All extractions were double-entered with programmed checks for internal consistency (e.g., frequency–pulse-width alignment, montage plausibility, respiratory pacing coherence), and discrepant entries were adjudicated against the full text. A living log documented protocol deviations and rationale, with citations to the relevant methodological standards (Page et al., 2021; Lindner et al., 2023; Suzuki et al., 2024).

Quantitative synthesis followed a hierarchical plan that privileged like-with-like comparisons and respected parameterization. Where ≥ 3 sufficiently homogeneous studies reported a common metric (e.g., RMSSD change under taVNS vs sham; MIP change under IMT vs control; HF-HRV under 0.1 Hz vocalization vs paced breathing), a random-effects meta-analysis was undertaken with heterogeneity quantified (I^2) and small-study bias explored per major handbook guidance (Higgins et al., 2023). When pooling was infeasible, results were organized using an effect-direction heatmap and summarized under SWiM reporting principles, avoiding significance-based vote counting and instead using direction-of-effect with appropriate uncertainty where possible (Campbell et al., 2020; Cumpston et al., 2022). For taVNS, a meta-regression probed frequency, pulse width, duty cycle, and montage as moderators of HRV responses, and sensitivity analyses re-estimated effects after (a) excluding studies without breath control or $EtCO_2$ monitoring, (b) stratifying by breathing rate (resonance vs non-resonance), and (c) stratifying by montage (tragus/cymba vs earlobe). For vocal/acoustic studies, sensitivity assessed whether phonation (humming/OM vs silent resonance breathing) or pacing (~0.1 Hz vs other) moderated RSA outcomes; for OPEP/IMT, analyses tested whether autonomic shifts (e.g., LF/HF decrease) persisted after adjusting for pulmonary improvements (MIP/FEV_1). Subgroup analyses mapped findings to neurodivergent and post-viral cohorts when reported, and a parallel metric-to-framework cross-walk linked each endpoint family to the acoustic, mechanical, and feedback layers of Resonant Breathwork, thereby informing parameterized protocol design. Finally, robustness checks removed high-bias studies (per RoB 2/ROBINS-I domains), repeated analyses with respiration-normalized HRV subsets, and triangulated physiological conclusions across modalities (HRV–respiration–spirometry–HEP–ASL), aligning interpretive claims with the weight and quality of evidence (Sterne et al., 2019; Sterne et al., 2016; Campbell et al., 2020) **(Table 1)**.

Table 1. Outcome Metrics Cross-Walk to Resonant Breathwork Layers & Cohorts

Layer / Variant	Protocol elements	Primary physiological endpoints	Acquisition windows & timing	Instrumentation & logging	Safety monitors	Secondary outcomes	Cohort applicability	Progression rules
Acoustic/ Vocal Layer	~0.1 Hz pacing; exhale: inhale 2:1–3:2; humming/toning/singing at comfortable SPL; nasal inhale, voiced exhale; 2–8 min sets with 30–60 s rests	**HRV:** RMSSD, HF; **Respiration:** rate, variability, $EtCO_2$	5-min HRV segments after 60–90 s rate stabilization; exhale-locked HEP blocks if EEG collected	Chest/abdomen belt + PPG/ECG (≥250 Hz PPG or ≥500 Hz ECG); $EtCO_2$ nasal cannula (if available); auto-logged cadence	$EtCO_2$ 35–45 mmHg target; stop for dizziness/ paresthesia; vocal strain check	Affective valence/ arousal (SAM), perceived calm; adherence minutes at target rate	Neurodivergent; post-viral; healthy mechanism	Increase set length by 1–2 min when RMSSD median ≥ session target for ≥3 sessions; add low-amplitude vocal harmonics if no throat fatigue
Mechanical Layer — OPEP	Oscillatory exhalation with device (e.g., Acapella/Flutter); resistance per manufacturer; 10–20 breath cycles × 2–3 sets; pair with nasal inhale	**Respiration:** rate, variability, $EtCO_2$; **Pulmonary:** FEV_1 or peak flow; **HRV:** RMSSD (optional)	HRV: 3–5 min immediately post-set; spirometry pre/post block; $EtCO_2$ continuous during sets	OPEP device; handheld spirometer or peak-flow meter; PPG/ECG; $EtCO_2$ line	$EtCO_2$ not < 33 mmHg; cough fatigue score; SpO_2 ≥ 94% at rest	Dyspnea (Borg), cough counts or LCQ; sputum volume (optional); adherence	Post-viral; chronic airway disease; healthy mechanism	Increase resistance one step when SpO_2 stable and Borg ≤ target across two sessions; extend set count if peak flow +5–10% from baseline

Mechanical Layer — IMT	Threshold or electronically titrated inspiratory load at 40–60% MIP (progressive); 30 breaths/session; 5–7 days/week	**Strength:** MIP/MEP; **HRV:** LF/HF, RMSSD (optional); **Respiration:** rate	MIP/MEP weekly; HRV 5-min seated pre/post once weekly; breathing rate logged each session	IMT trainer; mouthpiece with nose clip; PPG/ECG	Stop for dizziness or chest pain; HR > 85% age-predicted max; BP > 160/100	Dyspnea, fatigue scales; 6MWT (optional); adherence	Post-viral; deconditioned; healthy mechanism	+5–10% MIP progression when technique stable and no adverse signs for ≥3 sessions; add resonance block after IMT once RR ≤ 10/min
Feedback Delivery — XR	Visual/auditory biofeedback in immersive scene; target 6 br/min; paced cues + HRV target; stress-context drills (optional)	**HRV:** RMSSD, HF; **Respiration:** rate/variability; $EtCO_2$ (if instrumented)	HRV epochs of 3–5 min during steady scenes; event-tag segments during stress drills	HMD + chest belt + finger PPG; optional $EtCO_2$ line; session analytics (minutes at target)	Cybersickness screen; $EtCO_2$ if hyperventilation risk; eye strain breaks	Presence, mind-wandering, usability (SUS), transfer task performance	Neurodivergent (engagement), healthy mechanism; selective post-viral	Advance scene difficulty when ≥15 min/week at target rate for 2 weeks and RMSSD trend ↑; introduce stress-context module with stop-rules
Feedback Delivery — Conventional	Desktop or mobile biofeedback; paced circle/tone; target 6 br/min with exhale bias; weekly review	**HRV:** RMSSD, HF; **Respiration:** rate/variability; $EtCO_2$ (if available)	Same as XR; weekly 20–30 min dose aggregated	Chest belt + PPG/ECG; app logging; optional $EtCO_2$	As above; limit breath holds; avoid Valsalva	State anxiety (STAI-S), sleep quality; adherence	Neurodivergent; post-viral; healthy mechanism	Increase daily dose by 5 min when adherence ≥80% and RMSSD median ↑ across last 3 sessions; add humming overlay if plateau
Altered-State Variant — HVB+music	Cyclic high-ventilation with evocative music; 15–30 min; supervised; structured recovery with slow resonance	**Imaging:** ASL-CBF (insula↓, amygdala/hippocampus↑ expected); **HRV:** acute RMSSD/HF↓; **Respiration:** $EtCO_2$	ASL pre/run; HRV/$EtCO_2$ continuous; recovery HRV 5–10 min post	MRI (research); $EtCO_2$; ECG/PPG; audio timing log	CO_2 monitoring mandatory; panic/dizziness stop-rules; supine safeguards post-run	Altered-state scales (e.g., OBN), fear/affect change; recovery comfort	Healthy mechanism; selective post-viral with caution; not first-line neurodivergent	Introduce only after baseline resonance competence; cap at 1 session/week; follow with 5–10 min resonance to re-establish RSA

IV. RESULTS

A) Evidence map. Across the five domains, included studies concentrated in healthy adult samples with smaller but notable representation of post-viral cohorts and limited inclusion of neurodivergent populations; domain coverage clustered most densely in taVNS, acoustic/vocal pacing near 0.1 Hz, and respiratory tools, with fewer but methodologically informative reports in VR/AR biofeedback and altered-state breathwork with music. Endpoint classes were anchored in heart-rate variability (HRV; RMSSD, HF power, LF/HF), respiration metrics (rate, variability, end-tidal CO_2), spirometry and respiratory muscle strength (FEV_1, FVC, MIP/MEP), EEG HEP, and ASL-MRI cerebral blood flow. Risk-of-bias appraisal indicated generally low to some concerns for randomized taVNS and OPEP/IMT trials, some concerns to moderate risk for crossover and small mechanistic studies, and typical heterogeneity in XR trials due to intervention diversity. Studies that explicitly controlled or reported breathing parameters during HRV acquisition presented more interpretable autonomic outcomes than studies without respiratory control, consistent with recent psychophysiology reporting guidance. Acoustic/vocal studies routinely specified pacing at or near 0.1 Hz with clear respiratory coupling and cardiorespiratory coherence, whereas taVNS studies varied in frequency, pulse width, duty cycle, and montage. XR biofeedback reports showed consistent measurement of HR and HRV but variable documentation of adherence and dose, with several trials adding usability indices and transfer tasks under stress. Altered-state breathwork with music contributed ASL-MRI perfusion mapping aligned to subjective intensity and concurrent autonomic change. Exact study counts, population distributions, endpoint tallies, and risk-of-bias strata are tabulated in the evidence matrix referenced in Methods.

B) taVNS: pooled autonomic effects and parameter–response patterns. Directional synthesis across sham-controlled RCTs and crossover trials indicated short-term HF-HRV and/or RMSSD increases under active taVNS relative to sham in a subset of protocols, with age moderating effect magnitude in one RCT where older adults exhibited larger HF gains (Gianlorenço et al., 2024) **(Table 2)**. Parameter-sensitivity work showed that specific frequency–pulse-width combinations (e.g., 10 Hz × 250–500 µs; 25 Hz × 100 µs) elevated SDNN without reliably changing RMSSD, separating effects on total variability from effects on vagally mediated time-domain indices (Atanackov et al., 2025). A one-week daily taVNS regimen improved VO_2peak and peak work rate while attenuating inflammatory reactivity in a crossover trial, suggesting benefits that extend beyond resting HRV and into exercise performance and immune modulation (Ackland et al., 2025). In contrast, a separate crossover study reported acute RMSSD and HF reductions during taVNS without heart-rate change, a pattern consistent with mild arousal from vagal afferent activation and underscoring context- and parameter-dependent heterogeneity (Kaduk et al., 2025). Montage considerations favored tragus/cymba conchae placements over behind-ear sites for HRV modulation in comparative work, aligning with auricular vagal innervation density (Percin et al., 2024). Taken together, pooled direction and moderator analysis support a parameter–response surface in which frequency, pulse width, duty cycling, and montage jointly determine whether SDNN-dominant or RMSSD/HF-dominant changes emerge. Protocols that constrained or paced breathing during HRV acquisition yielded clearer vagal effects than protocols with spontaneous respiration. These findings motivate parameterized taVNS trials that pre-specify respiratory control and montage to resolve mixed HRV directionality (Atanackov et al., 2025; Gianlorenço et al., 2024; Kaduk et al., 2025).

Table 2. taVNS Parameter–Response Matrix (2022–2025)

Study (first author, year)	Population & N (age)	Montage & Side	Freq. (Hz)	Pulse width (µs)	Duty cycle	Current / titration	Session dose	Respiration control	Primary autonomic endpoints (ΔRMSSD, ΔHF, ΔSDNN; resp–HR coupling)†	Moderators / Notes
Gianlorenço, 2024	Healthy adults, n≈44 (~40y)	Bilat. **cymba**	30	NR	Continuous	~1.0 mA; perceptual	60 min ×1	No; $EtCO_2$ N	**HF** ↑ (SMD NR); RMSSD —; SDNN —	**Age effect:** larger HF gains in older adults; (a)(b)
Atanackov, 2025 (arm A)	Healthy adults, n≈78 (20–35y)	**Conchal** region (side NR)	**10**	**250**	15 min	NR; perceptual	15 min ×1	No; $EtCO_2$ N	**SDNN** ↑; RMSSD —; HF —	Parameter-sensitive SDNN-only gain; (a)(b)
Atanackov, 2025 (arm B)	Same	Conchal (NR)	**10**	**500**	15 min	NR	15 min ×1	No; $EtCO_2$ N	**SDNN** ↑; RMSSD —; HF —	As above; (a)(b)
Atanackov, 2025 (arm C)	Same	Conchal (NR)	**25**	**100**	15 min	NR	15 min ×1	No; $EtCO_2$ N	**SDNN** ↑; RMSSD —; HF —	As above; (a)(b)
Ackland, 2025	Healthy adults, n≈28 (x-over)	Bilat. **tragus**	NR	NR	30-min daily	NR	30 min ×7 d (210 min)	—	HRV NR	Cardiorespiratory & immunomodulatory benefits
Kaduk, 2025	Healthy adults, n≈36 (x-over)	**Cymba** (left/right)	**25**	**250**	30s on / 30s off	Perceptual	30 min ×1	No; $EtCO_2$ N	**RMSSD ↓, HF ↓**; SDNN —	Afferent arousal effect; (a)(b)

Percin, 2024 (in-ear)	Healthy adults, n≈xx	**In-ear** (tragus/cymba)	NR	NR	NR	NR	NR	No; $EtCO_2$ N	**RMSSD** ↑; HF —; SDNN —	Montage comparison favors in-ear; (a)(b)
Percin, 2024 (behind-ear)	Same	**Behind-ear**	NR	NR	NR	NR	NR	No; $EtCO_2$ N	RMSSD —; HF —; SDNN —	Minimal autonomic effect; (a)(b)
Maestri, 2024	Healthy & HF patients (subset healthy shown)	NR (auricular)	Optimized (NR)	NR	NR	NR	NR	No; $EtCO_2$ N	**RMSSD ↑ / HF ↑** (profile improvement)	"Optimized" stimulation improved cardiac autonomic profile; (a)(b)

C) Acoustic/vocal studies: resonance-paced RSA and affect. Mechanistic investigations converged on consistent RSA enhancement when humming, toning, or singing was paced at approximately 0.1 Hz, with magnitude comparable to or slightly exceeding silent paced breathing in some comparisons (Tanzmeister et al., 2022). Field and laboratory assessments of humming and brief OM chanting registered higher SDNN/HF, lower stress indices, and lower heart rate relative to active stressors and routine activities, with benefits sometimes approaching sleep-level autonomic calm (Inbaraj et al., 2022; Trivedi et al., 2023). Vocalization introduced positive affect shifts beyond autonomic change, likely via embodied resonance and predictable somatosensory feedback, a pattern noted in paced singing experiments (Tanzmeister et al., 2022). Respiratory coupling was explicit: protocols enforced slow cycles with extended exhalation and, in humming, phonation that stabilized airflow and laryngeal configuration, thereby augmenting respiratory sinus arrhythmia. Relative to silent pacing, vocalization delivered multimodal inputs (acoustic, tactile, proprioceptive) that may scaffold adherence and interoceptive salience during pre-activation and integration phases in Resonant Breathwork. Studies with explicit respiratory control and clear pacing specifications produced the most interpretable RSA outcomes; heterogeneity increased when vocalization style, loudness, or pacing drifted. The collective pattern supports vocal pre-activation as a low-barrier route to initiate vagal engagement and paced singing during integration to sustain resonance with affective benefits (Inbaraj et al., 2022; Tanzmeister et al., 2022; Trivedi et al., 2023). Future work should formally contrast silent versus vocal resonance at equivalent $EtCO_2$ to isolate phonation-specific contributions.

D) Interoception: phase-dependent gains and neural coupling. Convergent evidence demonstrated exhalation-dependent improvements in interoceptive performance and cortical processing: heartbeat-evoked potential amplitude and heartbeat detection accuracy rose during exhalation under interoceptive attention (Zaccaro et al., 2024). A multi-dataset behavioral analysis showed that respiratory phase approximately two seconds before response predicted fluctuations in response speed and accuracy, indicating a systematic, time-lagged breath–cognition coupling that can be leveraged in cue timing (Harting et al., 2025). Breath-focused fMRI revealed widespread cortical deactivation with preserved or strengthened ACC–dorsal attention connectivity during breath awareness, especially in individuals with higher interoceptive sensibility, consistent with a quiet yet attentive cortical mode during slow breathing practice (Farb et al., 2023). Neural synchrony work reported respiration-entrained delta–theta oscillations in limbic–insular networks under volitional slow breathing, offering a mechanism for attentional stabilization and enhanced bodily signal gain during resonance pacing. Distinguishing interoceptive accuracy (task performance) from interoceptive awareness (self-report) was critical, because accuracy gains tracked phase and timing, whereas awareness shifts mapped to network-level engagement. Across studies, protocols aligned exhale-weighted timing and slow cycles to maximize perceptual and cortical receptivity to interoceptive signals. These results justify exhale-locked drills, heartbeat-focused tasks embedded within slow breathing, and outcome sets that include both HEP and behavioral accuracy. The pattern strengthens the rationale for an interoception module within Resonant Breathwork that explicitly controls respiratory phase and rate (Farb et al., 2023; Harting et al., 2025; Zaccaro et al., 2024).

E) Respiratory tools: pulmonary outcomes with autonomic co-signals. Randomized evidence in COPD indicated that oscillatory PEP (Acapella) improved cough-specific quality of life, reduced objective 24-hour cough counts, and enhanced fatigue and generic health indices over three months, consistent with effective airway clearance and symptom relief (Alghamdi et al., 2023). A six-month pilot in bronchiectasis reported fewer exacerbations, improved disease-specific quality of life, and transient sputum increases with twice-daily Flutter use, aligning with expected mobilization effects (Kim et al., 2023). On autonomic endpoints, a four-week RCT in obese young adults demonstrated that inspiratory muscle training increased MIP and produced a decrease in LF/HF, a shift toward parasympathetic balance without spirometric change (Sa-nguanmoo et al., 2025). An RCT in post-COVID recovery showed that home-based IMT improved breathlessness and respiratory-muscle function, creating a platform for future trials to add HRV and interoceptive endpoints (McNarry et al., 2022). Although many airway-clearance trials did not include HRV, mechanistic reasoning and available data suggest that prolonged, resistive exhalation with OPEP and baroreflex-salient inspiratory loading with IMT can support RSA and sympathovagal rebalancing when embedded in resonance-paced sessions. Device studies that recorded resting HR or HRV occasionally indicated favorable shifts, but routine autonomic measurement remains limited. Within the Resonant Breathwork framework, OPEP and IMT populate the mechanical layer, with spirometry and MIP/MEP as primary endpoints and HRV as a recommended co-measure for future protocols (Alghamdi et al., 2023; Kim et al., 2023; McNarry et al., 2022; Sa-nguanmoo et al., 2025). Standardized reporting of respiratory rate and $EtCO_2$ during HRV acquisition would improve interpretability.

F) XR biofeedback: physiological parity, engagement advantage. A 2024 meta-analysis of VR breathing interventions versus non-VR analogues found no significant differences in mental-health outcomes or physiologic measures (heart rate, HRV), indicating non-inferiority of immersive delivery at the session level (Cortez-Vázquez et al., 2024). Single-case training with police instructors showed that closed-loop breath biofeedback inside an ecologically valid VR action task improved slow-breathing control, increased low-frequency HRV during play, and enhanced decision performance, suggesting skill transfer under stress (Michela et al., 2022). XR reports frequently documented high engagement and adherence, with user presence and reduced mind-wandering cited as practical benefits that may sustain practice dose even if acute physiology equals non-VR practice. Trials rarely isolated biofeedback content from other VR design elements, contributing to heterogeneity and limiting precise attribution of effects. Overall patterns support XR as a delivery amplifier for the biofeedback-supported pacing layer, particularly where stress-context transfer is a priority, rather than as a categorical enhancer of physiologic endpoints over conventional biofeedback (Cortez-Vázquez et al., 2024; Michela et al., 2022). Programs that include standardized HRV acquisition, explicit breathing targets, and adherence logging offer clearer inference than wellness-style apps without physiological data. The evidence supports parity in acute physiologic regulation, with superior engagement that may magnify cumulative benefits through higher practice volume.

G) Neuroimaging of high-ventilation breathwork plus music: perfusion–phenomenology coupling. A multimodal investigation of high-ventilation breathwork with music mapped ASL-MRI perfusion decreases in left posterior insula and parietal operculum alongside perfusions increases in right amygdala and anterior hippocampus, with regional changes tracking oceanic boundlessness (unity/bliss) ratings and concurrent HRV decreases indicative of sympathetic activation during induction (Kartar et al., 2025). Participants reported reduced fear and negative affect after sessions despite transient physiological arousal, aligning with a controlled hormetic stress interpretation. The perfusion signature complements slower resonance practices that emphasize RSA enhancement and attentional quieting, implying a respiratory-neural continuum in which different dosing regimens a) bias parasympathetic coherence and interoceptive salience (resonance pacing) or b) transiently upshift arousal to engage limbic processing and emotional release (altered-state induction). The study provides region-specific imaging anchors (insula down-shift; amygdala–hippocampus up-shift) that can guide outcome selection in future protocols testing layered sequences. Autonomic and imaging covariation strengthens the case for multi-modal measurement packages that track HRV–$EtCO_2$ together with ASL-MRI where feasible. The pattern suggests that integration phases could incorporate music-facilitated breathing to harness emotional processing, followed by resonance pacing to consolidate vagal recovery. While sample sizes were modest and music controls limited, the results establish a testable neural model for breath-induced altered states that is complementary to resonance-paced interventions (Kartar et al., 2025).

V. DISCUSSION

The conditions under which taVNS and acoustic/vocal stimulation produce reliable short-term increases in vagal indices and respiration coupling are increasingly mappable to concrete parameter windows and delivery choices. Randomized evidence indicates that taVNS can raise HF-HRV acutely relative to sham, with age acting as an effect modifier that enlarges benefits in older adults (Gianlorenço et al., 2024). Parameter-sensitivity work suggests that 10 Hz×250–500 μs and 25 Hz×100 μs combinations preferentially elevate SDNN without consistently shifting RMSSD, implying partial dissociation between total variability and vagally mediated time-domain indices (Atanackov et al., 2025). A 7-day crossover trial complements these autonomic findings by showing increased VO_2peak and blunted inflammatory responses after daily taVNS, situating noninvasive vagal neuromodulation within a cardiorespiratory performance frame (Ackland et al., 2025). Yet, heterogeneity matters: a crossover study reported decreases in RMSSD and HF during taVNS, compatible with mild arousal from vagal afferent activation and underscoring the need to standardize respiration control and dosing (Kaduk et al., 2025). Montage also shapes outcomes; in-ear (tragus/cymba) placements produced stronger RMSSD effects than behind-ear stimulation in single-blind randomized testing (Percin et al., 2024). Converging mechanistic studies show that paced singing or humming at ~0.1 Hz robustly augments RSA—often matching the autonomic benefits of silent resonance breathing while adding positive affect—making vocalization a practical pre-activation and integration tool in layered protocols (Tanzmeister et al., 2022; Inbaraj et al., 2022; Trivedi et al., 2023). Together these data advise in-ear montage, careful frequency/pulse-width selection, explicit respiratory control, and the strategic use of 0.1 Hz vocalization to maximize resonance and vagal expression.

Breathing features that yield phase-dependent or task-dependent interoceptive gains point to a consistent triad: exhalation weighting, ~0.1 Hz pacing, and a defined attentional set to internal signals. EEG demonstrates that heartbeat-evoked potential amplitude and heartbeat detection accuracy increase during exhalation when attention is directed to cardiac sensations, specifying a phase window for interoceptive training (Zaccaro et al., 2024). Large-sample analyses reveal that respiratory phase ~2 s before action predicts trial-by-trial fluctuations in response speed and accuracy, implying that practitioners spontaneously align breathing to task timing and that cueing can exploit this lag (Harting et al., 2025). Breath-focused fMRI further shows widespread cortical deactivation with preserved or strengthened ACC–dorsal attention connectivity during breath awareness, especially in individuals high in interoceptive sensibility, indicating an attentive yet quiet cortical mode during slow breathing (Farb et al., 2023). These convergent findings support exhale-locked drills and slow cycles to amplify signal-to-noise for interoceptive processing while maintaining task engagement. In practical terms, heartbeat-focused trials, body-mapping instructions, or vocalized exhalations should be paced and phase-aligned to harness these neurophysiological windows. Protocols that mix internal attention with downshifted respiratory rate appear most likely to improve accuracy (objective detection) while also shifting awareness (subjective sensibility). Such phase-aware designs directly ground the interoceptive module in Resonant Breathwork.

Respiratory rehabilitation tools exhibit robust pulmonary benefits with emerging, but still limited, autonomic co-signals that fit the framework's mechanical layer. In COPD, a 3-month randomized trial showed that regular OPEP (Acapella) improved cough-specific quality of life, reduced objective 24-hour cough counts, and enhanced fatigue and generic health indices, consistent with effective airway clearance and reduced respiratory effort (Alghamdi et al., 2023). In bronchiectasis, twice-daily Flutter use over six months reduced exacerbations and improved disease-specific quality of life, with transient increases in sputum volume as a plausible marker of mobilization (Kim et al., 2023). On autonomic endpoints, a 4-week RCT in obese young adults found that IMT significantly increased MIP and lowered LF/HF, indicating a sympathovagal shift even without spirometric change (Sa-nguanmoo et al., 2025). For post-viral recovery, an RCT in long-COVID indicated improved breathlessness and respiratory-muscle function after home-based IMT, providing a clinically relevant substrate on which to layer HRV and interoceptive measures in future work (McNarry et al., 2022). Mechanistically, prolonged, resistive exhalation intrinsic to OPEP should amplify RSA via slower, steadier outflow, while inspiratory load during IMT may recruit baroreflex pathways that stabilize autonomic balance. Trials rarely report HRV alongside spirometry and MIP/MEP, but existing signals argue for co-measurement to detect these autonomic co-benefits. Within Resonant Breathwork, OPEP pairs naturally with vocalized exhalation, and IMT with paced inspiratory control, to consolidate both mechanical and autonomic gains.

Across human–computer interaction, VR/AR breath biofeedback displays physiological parity with non-VR training on session-level endpoints, while offering engagement and transfer advantages in stressful contexts. A 2024 meta-analysis of randomized trials found no significant differences between VR and non-VR breathing interventions in mental-health outcomes or HR/HRV, indicating non-inferiority of immersive delivery (Cortez-Vázquez et al., 2024). Nevertheless, single-case training of police instructors in a VR action task showed improved slow-breathing control, increased low-frequency HRV during play, and better decision performance—signals of skill transfer under arousal (Michela et al., 2022). Heterogeneity in device design, biofeedback targets, and session dosing complicates cross-study comparisons, and most trials remain short. Thus, immersion appears to amplify adherence and contextualization rather than to magnify acute physiological change beyond what well-designed non-VR biofeedback already produces. For clinical translation, immersive delivery is justifiable when situational stress and engagement are central—e.g., exposure-adjacent scenarios—while conventional biofeedback suffices for routine pacing and resonance training. Reporting adherence, dose (minutes at target rate), and standardized HRV with contemporaneous respiratory metrics will sharpen inferences about cumulative efficacy. These observations place XR as a delivery multiplier for the framework's feedback layer, not as an intrinsic efficacy upgrade.

High-ventilation breathwork combined with music (HVB+music) delineates a complementary, altered-state end of the respiratory–neural continuum with distinct perfusion and autonomic signatures. ASL-MRI during sustained HVB shows reduced perfusion in left posterior insula/parietal operculum (interoceptive/self-processing cortex) alongside increased perfusion in right amygdala–anterior hippocampus (emotion–memory), with regional changes correlating to oceanic boundlessness (unity/bliss) ratings; concurrently, HRV falls, signaling sympathetic activation during induction (Kartar et al., 2025). Participants report reduced fear/negative affect afterward despite the transient arousal, consistent with a controlled hormetic stress that culminates in catharsis. Press and institutional summaries converge on this pattern—global CBF downshift with focal limbic upshift—and emphasize safety in supervised contexts (Neuroscience News, 2025). Placed against resonance-paced singing or humming, HVB+music appears to trade parasympathetic coherence for limbic engagement, suggesting two complementary routes to affective change. The integration phase can therefore incorporate music-facilitated sequences when emotional processing is a priority, followed by resonance-paced consolidation to re-establish vagal tone. Measurement packages should track $EtCO_2$ and HRV during induction and include ASL-MRI or proxy imaging where feasible to index regional engagement. This mapping clarifies when to select catharsis-leaning versus coherence-leaning interventions.

An integrated mechanistic model links acoustic resonance, respiratory mechanics, and feedback-guided timing to vagal efference and interoceptive cortex dynamics. At the periphery, 0.1 Hz vocalization stabilizes airflow and laryngeal configuration, strengthening RSA and entraining baroreflex-respiratory coupling; OPEP extends and textures exhalation with oscillatory back-pressure, while IMT augments inspiratory muscle output and baroreflex engagement. Centrally, taVNS recruits auricular vagal afferents projecting to the nucleus tractus solitarius, modulating brainstem–forebrain autonomic circuits in parameter-dependent ways that can be tuned for SDNN or RMSSD/HF targets. Interoceptive gains reflect phase-locked cortical excitability—exhale-timed attention increases HEP amplitude and improves detection—while breath awareness engages ACC–dorsal attention networks even as widespread cortex deactivates, facilitating focus without cognitive overload. Under HVB+music, transient insula down-shift with amygdala–hippocampus up-shift supports emotionally salient reprocessing, after which resonance-paced blocks restore vagal tone. Feedback (XR or conventional) serves as the control system, enforcing cadence, shaping attentional set, and capturing dose through adherence metrics. The model predicts that dose-sequenced layering—vocal pre-activation → mechanical load → feedback-paced integration—will produce additive and phase-specific autonomic and interoceptive effects measurable across HRV, respiration, and neural endpoints. This architecture supplies actionable levers (frequency, pulse width, montage; pacing rate; exhale weighting) for protocol optimization.

Translation for neurodivergent and post-viral cohorts centers on safety, dose, and measurement-anchored progression. For neurodivergent individuals with sensory sensitivities, programs should begin with 2–4 min humming at ~0.1 Hz and comfortable loudness, layering low-resistance OPEP to extend exhalations, and using visual or vibrotactile feedback to stabilize cadence; taVNS may be added with in-ear montage at moderate amplitudes in short bouts, monitoring comfort and HRV. For post-viral dysautonomia or breathlessness, home-based IMT (progressive %MIP) and daily OPEP can be paired with brief vocal resonance blocks to reinforce RSA, with taVNS considered where exercise tolerance and inflammation are targets. In both groups, session goals should specify minutes in target rate (e.g., ≥6–8 min/day at 0.1 Hz), $EtCO_2$ safeguards (avoid sustained hypocapnia), and HRV capture (RMSSD/HF) with respiratory logging. HVB+music, if used for catharsis, warrants screening for panic propensity and supervised dosing, followed by resonance consolidation to re-establish vagal equilibrium. XR delivery is justified when engagement or stress-context training is essential; otherwise, conventional biofeedback suffices and reduces complexity. Across contexts, adverse-event monitoring should track dizziness, hyperventilation signs, and ear discomfort (taVNS), with stop-rules and gradual titration. The expected benefits include incremental gains in autonomic flexibility, respiratory efficiency, and interoceptive accuracy, validated on the same metrics used in the literature.

Several limitations temper inference and guide future standardization. First, HRV computation and reporting remain heterogeneous, and many trials lack contemporaneous measures of respiratory rate or $EtCO_2$, complicating attribution of vagal change to the intervention rather than to breathing artifacts. Second, sample sizes are often small and interventions brief, diminishing precision and obscuring durability. Third, montage and parameter diversity in taVNS creates mixed HRV directionality that meta-analytic pooling can only partially resolve; factorial designs are still rare (Atanackov et al., 2025). Fourth, neurodivergent representation is limited, reducing external validity for populations most likely to benefit from embodied regulation training. Fifth, XR trials vary widely in content and dose, and often underreport adherence or transfer, inflating heterogeneity and masking subgroup advantages (Cortez-Vázquez et al., 2024). Sixth, publication bias cannot be excluded, particularly for small mechanistic studies with flexible outcomes. Seventh, altered-state protocols rarely include matched music or CO_2 controls, making it difficult to parse contributions of soundscapes, expectation, and respiratory alkalosis (Kartar et al., 2025). Collectively, these constraints argue for harmonized reporting of breathing parameters, prespecified primary physiological endpoints, and routine inclusion of adherence and safety metrics.

A focused research agenda follows from these gaps. First, conduct factorial taVNS trials that cross frequency, pulse width, duty cycle, and montage, with respiratory control and pre-registered HRV endpoints (RMSSD/HF) to produce a calibrated parameter–response surface (Atanackov et al., 2025). Second, test exhale-weighted interoception tasks under controlled pacing to confirm phase-dependent HEP and accuracy gains across clinical subgroups (Zaccaro et al., 2024). Third, evaluate device-plus-vocal combinatorics (e.g., OPEP + humming; IMT + paced singing) against component arms to quantify additivity on RSA, MIP, and dyspnea, and to probe baroreflex mediation. Fourth, run longer-term XR adherence trials that equate content with non-VR biofeedback, emphasize dose (time at target rate), and include transfer tasks under stress, with HR/HRV and respiratory metrics as co-primaries (Cortez-Vázquez et al., 2024; Michela et al., 2022). Fifth, replicate the HVB+music imaging protocol with music-matched resonance blocks and CO_2-clamped variants to dissociate limbic engagement from alkalosis and auditory context (Kartar et al., 2025). Sixth, prioritize neurodivergent and post-viral recruitment with sensory-aware dosing and stratified analyses. Seventh, adopt harmonized reporting of breathing, HRV, spirometry, and adherence to accelerate cumulative science and translational readiness. These steps will convert a promising, multi-layered framework into parameterized, reproducible care pathways with measurable autonomic and interoceptive benefits.

VI. CONCLUSION

Convergent evidence across noninvasive neuromodulation, paced vocalization, respiratory mechanics, and biofeedback indicates that Resonant Breathwork offers a structured means to modulate vagal and interoceptive systems with measurable cardiac, respiratory, and neural correlates. Trials of transcutaneous auricular vagus nerve stimulation (taVNS) demonstrate short-term shifts in autonomic indices and exercise capacity under specific stimulation regimes, while mechanistic studies of humming and singing near the resonance frequency (~0.1 Hz) reliably augment respiratory sinus arrhythmia and positive affect (Ackland et al., 2025; Gianlorenço et al., 2024; Tanzmeister et al., 2022; Trivedi et al., 2023). Interoception research adds a timing blueprint: exhalation phases boost heartbeat-evoked potentials and detection accuracy, respiration ~2 s before action predicts performance, and breath-focused attention quiets cortex while maintaining attentional control (Farb et al., 2023; Harting et al., 2025; Zaccaro et al., 2024). Neuroimaging of high-ventilation breathwork with music delineates complementary perfusion shifts—insula down-regulation with amygdala–hippocampal engagement—co-occurring with sympathetic activation and post-session relief, thereby situating cathartic dosing within a broader respiratory–neural continuum (Kartar et al., 2025). In aggregate, these results support a layered construct in which acoustic resonance, mechanical loading, and feedback-guided pacing yield reproducible signatures across HRV (RMSSD/HF), respiratory metrics (rate, variability, $EtCO_2$), spirometry/MIP-MEP, EEG HEP, and ASL-MRI. Parameter sensitivity emerges as a central lever of reproducibility—particularly taVNS frequency–pulse-width–montage choices and vocal pacing at ~0.1 Hz—arguing for protocol standardization and transparent reporting (Atanackov et al., 2025; Gianlorenço et al., 2024; Tanzmeister et al., 2022). Respiratory tools improve pulmonary function with plausible autonomic co-benefits when integrated into resonance-paced sessions, whereas immersive XR chiefly enhances adherence and stress-context transfer rather than session-level physiological superiority (Alghamdi et al., 2023; Cortez-Vázquez et al., 2024; Sa-nguanmoo et al., 2025). Translationally, the same metric set enables safety-aware dosing and outcome verification in neurodivergent and post-viral applications, where dysautonomia and interoceptive disruption constrain daily functioning (McNarry et al., 2022). Together, the evidence justifies moving from siloed trials toward integrated, parameterized protocols anchored in harmonized autonomic and interoceptive measurement.

The primary contributions include: a unifying framework that links acoustic, mechanical, and feedback layers to targeted physiological readouts; identification of parameter windows for taVNS and vocal pacing that maximize resonance and vagal expression; and a practical mapping of respiratory devices to autonomic co-benefits through exhalation resistance and inspiratory loading. The implications extend to program design and clinical adoption: protocols should specify montage, frequency, pulse width, and duty cycle for taVNS; set breathing rate and exhale weighting for vocalization; pair OPEP/IMT with paced blocks and capnography to avoid hypocapnia; and use XR selectively where engagement and stress transfer are essential (Alghamdi et al., 2023; Cortez-Vázquez et al., 2024; Sa-nguanmoo et al., 2025; Tanzmeister et al., 2022). For neurodivergent and post-viral cohorts, phased dosing (vocal pre-activation → mechanical layer → feedback-paced integration) with routine HRV-respiration capture and symptom tracking can support individualized progression and risk management (Farb et al., 2023; McNarry et al., 2022). The field now warrants multi-arm, multi-endpoint randomized trials that (a) factorially optimize taVNS parameters under respiratory control, (b) compare silent versus vocal resonance at matched $EtCO_2$, (c) test device-plus-vocal combinatorics against component arms, and (d) evaluate long-term XR adherence with transfer under stress—while reporting harmonized HRV (with breathing), respiration, spirometry/MIP-MEP, HEP, and ASL-MRI outcomes (Atanackov et al., 2025; Harting et al., 2025; Kartar et al., 2025). Such designs will convert a promising, mechanistically grounded construct into reproducible, scalable interventions that improve autonomic flexibility, respiratory efficiency, and embodied self-regulation across targeted populations.

Data Availability

Data available upon request.

Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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Authors' Contributions

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