Clinical Neuropsychiatry (2025) 22, 3, 169-184

INVITED PAPER

POLYVAGAL THEORY: CURRENT STATUS, CLINICAL APPLICATIONS, AND FUTURE DIRECTIONS

Stephen W. Porges

Abstract

Polyvagal Theory proposes an evolutionarily informed neurophysiological framework for understanding how the autonomic nervous system supports social engagement, emotional resilience, and adaptive physiological responses. At its core, the theory emphasizes a hierarchical organization of autonomic states mediated by the vagus nerve, highlighting the unique role of the ventral vagal complex in facilitating social behavior and physiological flexibility through mechanisms such as neuroception, co-regulation, and dissolution. This paper reviews the empirical foundations of Polyvagal Theory, addresses methodological critiques – particularly regarding anatomical specificity and respiratory sinus arrhythmia (RSA) – and consolidates recent advances in autonomic measurement. Furthermore, it explores wide-ranging clinical implications across diverse conditions including trauma, chronic pain, autism, developmental disorders, and mood disorders. Finally, the paper advocates for applying a "science of safety" in clinical practice, education, and public health, offering future directions for research, clinical practice, and the systemic design of institutions that support physiological safety at scale.

Key words: polyvagal theory, ventral vagal complex, neuroception, vagal efficiency, trauma, autonomic nervous system

Stephen W. Porges[1]
[1]Traumatic Stress Research Consortium, Kinsey Institute, Indiana University

OPEN ACCESS

Citation: Porges, S. W. (2025). Polyvagal Theory: Current Status, Clinical Applications, and Future Directions. *Clinical Neuropsychiatry, 22*(3), 175-191.

doi.org/10.36131/cnfioritieditore20250301

Funding: None.

Competing interests: None.

Corresponding author
Email: sporges@gmail.com

1. Introduction: from theory to perspective

When I first introduced Polyvagal Theory in 1994, my goal was to provide a neurophysiological model that could explain how the autonomic nervous system – particularly the vagus nerve – shaped our capacity for emotion, behavior, and social connection. What began as a scientific effort to understand the body's response to challenge has evolved into a broader perspective on how safety, regulation, and relationships are embedded in our biology.

Over the past three decades, this theory has been embraced not only by researchers and clinicians, but by educators, health professionals, trauma survivors, and social justice advocates. Polyvagal Theory continues to grow in both empirical grounding and transdisciplinary relevance, offering a language for describing how our nervous system navigates between states of defense and connection.

The heart of the theory is a simple yet transformative idea: our ability to feel safe and connect with others is biologically embedded in the structure and function of our autonomic nervous system. When we understand behavior through the lens of neurophysiological state, we shift from judgment to curiosity, from pathology to adaptation.

In this paper, I reflect on the current status of Polyvagal Theory, its foundational neuroanatomy, and its expanding clinical and societal applications. I respond to critiques and misinterpretations that have emerged and offer a forward-looking view of where the theory can inform science, healing, and policy. Building on the foundation established in *Polyvagal Perspectives* (2024), this paper continues the effort to articulate a science of safety – one that can guide both individual well-being and collective transformation. The following sections review the scientific foundations of the theory, its evolutionary and developmental origins, and the distinctive features of mammalian autonomic regulation.

2. Scientific foundations: neurophysiology and evolution

2.1 Developmental and phylogenetic evidence

The developmental and evolutionary trajectory of the ventral vagal complex is central to its role in the social engagement system. The ventral vagal complex is not merely a newer layer of anatomy – it is an evolutionary repurposing of ancient brainstem circuits (Porges, 2001). During vertebrate evolution, cardioinhibitory neurons migrated ventrally from the dorsal motor nucleus of the vagus (DMNX) to the nucleus ambiguus (NAmb) (Porges, 2023). This migration, unique to mammals, allowed for the development of a myelinated vagus capable of supporting the dynamic regulation required for nursing, vocalization, and caregiving (Porges, 2023). These anatomical changes are paralleled in embryological development, where the cranial nerves involved in the social engagement system − V, VII, IX, X, and XI − arise from the pharyngeal arches (Moore et al., 2018). Although they are represented by distinct motor nuclei, their shared developmental origin supports their integrated function in facial expression, vocal modulation, ingestion, and orienting behaviors (Porges, 2023).

In mammals, these neural structures are coordinated by the ventral vagal complex (VVC) to regulate state-dependent social behaviors, such as nursing, bonding, vocal communication, and facial prosody (Porges, 2007). This system is operational at birth, enabling suck–swallow–breathe coordination and forming the physiological substrate for sociality and emotional coregulation (Porges & Furman, 2011).

This evolutionary adaptation underscores the role of the vagus nerve in creating the foundation for social and emotional regulation, where physiological responses are tied to social engagement behaviors (Porges, 2003). The neural coupling of these systems facilitates dynamic interactions that are essential for infant survival and development, supporting the integration of autonomic and social behaviors within the emerging mammalian framework (Porges, 2007). Building on this developmental foundation, the next section compares mammalian and reptilian neural architectures relevant to autonomic regulation and social engagement.

2.2 Comparative neuroanatomy, autonomic integration, and the social engagement system

To further clarify the uniqueness of mammalian autonomic regulation, this section presents a comparative analysis of the neural structures underlying autonomic and social engagement systems in mammals and reptiles. Critics of Polyvagal Theory (e.g., Grossman & Taylor, 2007; Grossman, 2023; Taylor et al., 2022) often conflate anatomical homology with functional equivalence, erroneously assuming that the presence of a NAmb in reptiles implies autonomic capacities similar to those observed in mammals. This reflects a misunderstanding of comparative neuroanatomy, which distinguishes between *homologous structures* − those with a shared evolutionary origin − and *analogous functions*, which may arise independently across lineages. Grossman and Taylor's logic incorrectly assumes that shared features such as cardioinhibitory vagal pathways imply shared function, overlooking the evolutionary reorganization and diversification of these systems.

Polyvagal Theory challenges this assumption by emphasizing that evolution repurposes conserved anatomical substrates for newly emergent functions. While reptiles and birds retain a brainstem region identified as the NAmb, they lack the myelinated cardioinhibitory vagal efferents that define mammalian autonomic flexibility and social engagement. In mammals, a ventral migration of cardioinhibitory neurons from the dorsal motor nucleus of the DMNX to the NAmb gave rise to a myelinated cardioinhibitory vagal subsystem − an evolutionary innovation enabling adaptive cardiac regulation during social engagement.

This reorganization forms the foundation of the VVC − a mammal-specific subsystem that integrates autonomic regulation with motor pathways controlling the face, head, and vocal tract via cranial nerves V, VII, IX, X, and XI. The VVC enables context-sensitive cardiac regulation in coordination with facial expressivity and vocal prosody, providing the neurophysiological basis for co-regulation, prosocial behavior, and relational safety.

This evolutionary transition is recapitulated during embryological development, where cardioinhibitory neurons migrate ventrally from the DMNX to the NAmb. This ontogenetic trajectory mirrors the phylogenetic transformation that gave rise to the mammalian VVC, reinforcing the idea that developmental processes echo evolutionary adaptations.

Crucially, this neuroanatomical integration underlies two defining mammalian features: the coordination of suck–swallow–breathe patterns that enable nursing, and the production of vocal prosody − the modulation of pitch, rhythm, and tone that conveys affective intent and signals safety. Both behaviors require the precise, state-dependent coordination of cranial nerves IX (glossopharyngeal), X (vagus), and XI (accessory), which regulate the larynx, pharynx, and soft palate. This shared circuitry reflects a functional continuity between early-life feeding behaviors and later-emerging social communication.

Within the Polyvagal framework, the ability to nurse and to vocalize with prosodic nuance both reflect the same underlying brainstem-visceral integration that supports sociality. While additional cranial nerves V (trigeminal), and VII (facial) contribute to articulation, jaw control, and facial expression, it is the orchestrated activity of IX, X, and XI that enables both the rhythmic motor patterns necessary for nursing and the dynamic modulation of the voice that supports co-regulation and relational engagement.

Importantly, mammals and reptiles did not evolve along a linear continuum. Rather, they diverged from a common amniote ancestor along separate evolutionary trajectories: mammals from synapsids and reptiles from sauropsids. This branching produced lineage-specific innovations and functional repurposing of conserved structures. As such, attempts to infer mammalian autonomic or social function from reptilian anatomy disregard basic principles of phylogenetic divergence. In reptiles, the NAmb retains a somatomotor role but lacks integration with myelinated cardioinhibitory vagal control. While some reptilian species exhibit limited vocalization, they do not possess the mammalian capacity for coordinated, prosodic signaling or for suckling − behaviors that depend on the evolutionarily novel coupling of autonomic regulation with brainstem motor output.

As summarized in **table 1**, these neuroanatomical, physiological, and behavioral differences delineate the unique features of the mammalian autonomic and social engagement systems when compared to those of reptiles.

Transcriptomic studies reinforce this divergence. Single-nucleus RNA sequencing in adult mice has revealed that neurons within the mammalian NAmb express distinct gene profiles associated with myelination (e.g., *Mbp*, *Myrf*), neuropeptide signaling, and synaptic plasticity (e.g., *Snap25*). These expression patterns distinguish the NAmb from neighboring brainstem nuclei and indicate its specialized role in autonomic regulation, vocalization, and ingestive behaviors (Cao et al., 2019; Liu et al., 2024). These molecular specializations provide strong evidence that mammalian vocal prosody and suck–swallow–breathe coordination are not merely structural adaptations, but genetically supported innovations in brainstem organization that enable dynamic social engagement.

As this comparative perspective demonstrates, mammalian autonomic organization is uniquely structured to support flexible, state-dependent social engagement − a theme further developed in the next section's analysis of evolutionary innovations.

Table 1. *Comparative Features of Mammalian and Reptilian Autonomic and Social Engagement Systems. This summarizes key neuroanatomical, genetic, and behavioral distinctions relevant to Polyvagal Theory*

Feature	Mammals	Reptiles
Phylogenetic lineage	Synapsids (mammalian lineage)	Sauropsids (reptilian lineage)
Cardioinhibitory vagal origin	Both dorsal motor nucleus of the vagus (DMNX) and nucleus ambiguus (NAmb) due to a ventral migration of cardioninhibitory neurons from DMNX to NAmb	Predominantly located in DMNX
Vagal fiber type	Myelinated preganglionic fibers in the NAmb and unmyelinated preganglionic fibers in the DMNX	Unmyelinated preganglionic fibers predominantly in DMNX
Nucleus ambiguus function	Integrates parasympathetic and somatomotor outputs	Primarily somatomotor outputs
Cardiac regulation	Rapid, state-dependent modulation via myelinated vagus	Slower, tonic modulation via unmyelinated vagus
Facial musculature and expressivity	Richly innervated; supports social signaling (CN VII)	Minimal; limited capacity for expressive signaling
Vocal communication	Affective prosody via CN IX–X–XI; supports co-regulation	Limited vocalizations only some species
Integrated social engagement system	Involving CN V, VII, IX, X, XI; supports co-regulation and safety	Absent; lacks coordination between cranial and autonomic systems
Gene expression in the nucleus ambiguus (NAmb)	High expression of myelination and neuropeptide genes (e.g., *Mbp*, *Myrf*, *Snap25*)	Minimal expression; consistent with unmyelinated physiology
Behavioral flexibility	High; enables rapid adjustment of state to social context	Low; defensive behaviors more stereotyped
Neuroception of safety	Present; supports inhibition of defense and co-regulation	Absent; lacks adaptive autonomic modulation based on context

2.3 Comparative evidence and evolutionary implications

To understand the unique features of mammalian autonomic regulation, it is essential to consider the evolutionary divergence between mammals and reptiles and its implications for behavioral and physiological adaptation. Mammals and reptiles did not evolve along a linear continuum; rather, they diverged from a shared amniote ancestor, leading to distinct evolutionary lineages – mammals from synapsids and reptiles from sauropsids (Pough et al., 2023). While both retained conserved elements of the autonomic nervous system, mammals adapted these structures to support greater autonomic flexibility in service of social behavior.

A pivotal mammalian innovation was the emergence of myelinated cardioinhibitory vagal efferents originating in the NAmb (Porges, 2007; Liu et al., 2024). These fibers enabled the rapid, state-dependent modulation of visceral function, allowing the autonomic nervous system to respond dynamically to environmental and relational cues. This adaptation marked a fundamental shift from slow, homeostatic regulation toward flexible physiological support for social engagement, co-regulation, and emotional expression (Porges, 2001, 2007, 2023).

Functionally, this evolutionary development supports behaviors that are both biologically essential and socially meaningful − such as nursing, vocal prosody, and affective communication. These behaviors depend on finely tuned coordination between brainstem autonomic and motor systems, illustrating how visceral regulation and social signaling became tightly integrated in mammals (Porges, 2023; Cao et al., 2019).

VVC − defined by its myelinated cardioinhibitory vagal efferents − is not merely an anatomical feature, but a key evolutionary development that provides the structural and functional substrate for mammalian sociality. By enabling rapid, state-dependent shifts in autonomic activity, the VVC allows mammals to coordinate visceral regulation with behavioral and relational engagement. This capacity for autonomic flexibility underlies the dynamic regulation of connection, safety, and co-regulation, and forms the neurophysiological foundation of Polyvagal Theory, which emphasizes that physiological state is inseparable from emotional well-being and social behavior (Porges, 2023).

Having established these evolutionary distinctions, the following section examines the core neurophysiological mechanisms that differentiate mammalian from non-mammalian autonomic integration, with special attention to the origins and measurement of respiratory sinus arrhythmia (RSA).

2.4 Respiratory frequency in RSA, the common cardiopulmonary oscillator, and the neurophysiological foundations of Polyvagal Theory

Polyvagal Theory offers a phylogenetically informed model of autonomic regulation, positing that RSA is not a mechanical artifact of respiration, but a neurophysiological marker of rhythmic vagal outflow originating in the NAmb. RSA frequency parallels respiratory rhythm because both are governed by a central pattern generator − often termed the common cardiopulmonary oscillator − located in the brainstem (Richter & Spyer, 1990).

This oscillator organizes respiratory and cardiac output via rhythmic input from medullary respiratory circuits, notably the pre-Bötzinger complex and nucleus tractus solitarius (NTS), to both the phrenic nerve (driving inspiration) and cardiac vagal neurons in the NAmb producing RSA. The phrenic nerve, arising from cervical roots C3–C5, innervates the diaphragm and controls respiration in synchrony with each cycle. Neurophysiological studies demonstrate that the same medullary pattern generator entrains cardiac vagal efferents, resulting in a tightly coupled, phase-locked relationship between breathing and respiratory rhythms in heart rate (Richter & Spyer, 1990; Mendelowitz, 1999; Smith et al., 1991; Neff et al., 2003). These insights provide the foundation for reframing RSA as a central, rather than peripheral, biomarker of autonomic regulation − a theme critical to Polyvagal Theory's translational relevance.

Cardiac vagal neurons in the NAmb are inherently silent unless activated by this central, respiration-linked input, producing phasic vagal output only in response to oscillator-driven excitation. Thus, RSA frequency reflects the intrinsic rhythm of this central mechanism − not peripheral feedback or mechanical inflation, as has been erroneously claimed by some critics (Grossman & Taylor, 2007). Animal studies confirm that bursts of phrenic nerve activity correspond with bursts of cardiac vagal efferent activity, supporting the model of a shared central oscillator.

This mechanism, articulated in Polyvagal Theory since its earliest publications (Porges, 1995; 2007; 2023), identifies the NAmb as the source of myelinated cardioinhibitory output in the VVC − a system unique to mammals and absent in reptiles producing mammalian RSA. These fibers, derived through neuroanatomical migration, endow mammals with the capacity for rapid, reversible cardiac modulation − a prerequisite for adaptive, co-regulated social behavior and behavioral flexibility (Porges, 2007, 2023).

The inclusion of the phrenic nerve as a direct effector of the common cardiopulmonary oscillator underscores the integrated nature of respiratory and cardiac control in mammals, providing a neurophysiological foundation for the dynamic coupling of physiological state and social behavior that defines Polyvagal Theory. This central coordination enables mammals to efficiently shift physiological states in response to environmental and social cues, supporting resilience and engagement in ways not observed in non-mammalian vertebrates.

This integrative, mammalian-specific organization of the common cardiopulmonary oscillator is fundamental to understanding RSA as a central neurophysiological signal. The methodological implications of this mechanism − and how it can be quantified − are addressed in the following section. These neurophysiological insights into the origins of RSA create an opportunity to reconsider how central autonomic integration is measured − an issue explored through the development of weighted coherence in the next section.

2.5 Quantifying central autonomic integration: the development and reinterpretation of weighted coherence

The development of weighted coherence as a metric for central autonomic integration (Porges et al., 1980) represented a critical methodological advance in the study of cardiorespiratory physiology. Using cross-spectral analysis, weighted coherence assesses the phase consistency between respiratory and heart rate oscillations, weighting this consistency by the variance of heart rate at each respiratory frequency. Unlike traditional RSA amplitude measures (e.g., Lewis et al., 2012), this dynamic, systems-level index reveals both individual and context-dependent differences in autonomic function.

Empirical studies have validated the use of weighted coherence as a biomarker: higher coherence predicts greater anticipatory heart rate deceleration during attention tasks (Porges & Coles, 1982), and stimulant administration modulates coherence in parallel with behavioral changes (Porges et al., 1981). Pharmacological research further demonstrated that while RSA amplitude declines under vagal blockade, weighted coherence remains stable − a dissociation best explained by a central rather than a peripheral origin for respiratory–heart rate coupling (Porges, 1986).

Initially, weighted coherence was interpreted as a measure of parasympathetic (vagal) outflow. However, empirical dissociation observed under cholinergic blockade prompted a shift in interpretation. With the further development of Polyvagal Theory and the introduction of vagal efficiency, it has become clear that weighted coherence, similar to vagal efficiency reflects central brainstem coordination, as they remain robust even under pharmacological challenge (Porges, 1986, 2024). Weighted coherence specifically quantifies the efficiency of the central cardiopulmonary oscillator, integrating the pre-Bötzinger complex, nucleus tractus solitarius (NTS), and NAmb (Smith et al., 1991; Richter & Spyer, 1990, 2001; Mendelowitz, 1999). Thus, the metric offers a direct, functional assessment of the neurophysiological processes underlying cardiorespiratory integration.

Methodological advances such as weighted coherence challenge approaches advocated by Grossman and Taylor (2007), who argue for statistical correction of RSA for respiratory variables under the erroneous assumption that RSA is a mechanical artifact of breathing. As demonstrated in the previous section, RSA and respiration are co-modulated by a central oscillator unique to mammals. Attempts to statistically remove respiration from RSA distort the neurophysiological signal and eliminate meaningful variance tied to central autonomic control. These critiques inaccurately frame Polyvagal Theory as lacking a neuroscientific basis and misrepresent the central role of the NAmb in RSA generation (Porges, 2023).

Weighted coherence thus provides a robust, systems-level index of central autonomic integration, clarifying key neurophysiological and evolutionary questions (Porges & Bohrer, 1980; Richter & Spyer, 1990). The broader implications of these innovations for both comparative biology and clinical science are considered in the next section.

2.6 Evolutionary, clinical, and translational implications of methodological innovation

The validation of central metrics such as weighted coherence and vagal efficiency (Porges, 1986, 2023, 2024) has profound implications for both evolutionary biology and clinical science. By providing direct indices of central autonomic regulation, these measures clarify the origins and functional significance of RSA, while also advancing the understanding of mammalian-specific adaptations in autonomic control.

In mammals, myelinated cardioinhibitory fibers within the ventral vagal complex – rhythmically gated by medullary respiratory circuits – enable rapid, context-sensitive modulation of cardiac output (Porges, 1995, 2007, 2023; Mendelowitz, 1999; Neff et al., 2003). This innovation distinguishes mammals from reptiles, where vagal cardioinhibitory control is mediated primarily by unmyelinated fibers from the DMNX, and where a coordinated cardiopulmonary oscillator is absent (Richter & Spyer, 1990; Porges, 2023). Consequently, respiratory–heart rate interactions, as a marker of central cardioinhibitory gating, are minimal or absent in reptiles. In these species, autonomic regulation is coupled primarily to meet the metabolic demands of movement and remains largely decoupled from social interaction (Porges, 2007, 2021; Liu et al., 2024).

The translational value of central autonomic indices is evident in their application as robust, non-invasive biomarkers for autonomic function across a range of clinical contexts, including trauma, anxiety, autism, and other neurodevelopmental or psychiatric conditions (Porges et al., 1981; Porges, 1976, 2023, 2024). These metrics are effective in naturalistic and ambulatory settings, and their robustness under pharmacological challenge underscores their research and clinical value (Porges, 1986, 2024).

Despite calls by Grossman for statistical correction of RSA for respiration (e.g., Grossman & Taylor, 2007) their arguments fail to acknowledge the evolutionary distinctiveness and the central, brainstem-mediated mechanism of RSA (Richter & Spyer, 1990, 2001; Porges, 2023, 2024). By reframing RSA through the lens of Polyvagal Theory and employing validated central metrics, a coherent foundation is established for future translational research, clinical diagnostics, and therapeutic applications. By focusing on systems-level markers like weighted coherence, Polyvagal Theory advances both evolutionary understanding and the development of more effective interventions for conditions rooted in disrupted autonomic regulation.

2.7 Popularization and theoretical fidelity

Beyond methodological and translational debates, another important dimension of Polyvagal Theory's influence concerns its reception and application in popular and clinical contexts. A nuanced critique of Polyvagal Theory concerns its popularization in psychotherapy, coaching, and wellness communities. Some argue that metaphorical language risks diluting scientific integrity. Although conceptual precision is essential. In *Polyvagal Perspectives* (2024), I emphasized that while metaphors can enhance accessibility, this must be balanced with a commitment to scientific rigor. Core constructs such as neuroception, hierarchical state regulation, and dissolution are not metaphors – they are empirically grounded hypotheses derived from evolutionary neuroscience.

Although academic critiques have often misconstrued foundational principles – particularly by mislabeling scientific constructs as metaphorical – many clinicians, even when relying on translational language (i.e., language adapted for clinical accessibility), have accurately applied these principles in practice. Notably, some neuroscientific critics – such as Grossman and Taylor – have mischaracterized these principles. Their critiques often overlook the hierarchical structure of the autonomic nervous system or misunderstand the role of neuroception in mediating physiological state shifts. In contrast, many clinicians have adopted these principles with conceptual accuracy and therapeutic utility.

While translational language is sometimes necessary in clinical settings, the challenge is to ensure such communication remains faithful to the underlying science. Simplified models that foster self-understanding and compassion can be powerful tools, provided they preserve theoretical coherence, respect neurophysiological specificity, and ultimately enhance clinical effectiveness – especially in trauma recovery and emotion regulation. Maintaining this balance ensures that Polyvagal Theory remains both accessible and anchored in empirical science – a foundation that supports its ongoing evaluation through rigorous hypothesis testing.

2.8 Falsifiability and predictive power

Another line of critique suggests that Polyvagal Theory lacks falsifiability or overextends its explanatory reach. This critique is misguided. Contrary to claims that Polyvagal Theory lacks falsifiability, the theory has generated a range of specific, testable predictions. In fact, Polyvagal Theory has yielded a number of explicit, falsifiable predictions, such as the following:

1. The hierarchical recruitment of autonomic states under threat, proceeding from the ventral vagal complex (social engagement system) to

sympathetic activation (mobilization), to dorsal vagal shutdown (immobilization) (e.g., Porges, 2001; Reed et al., 1999).
2. The influence of social cues on vagal tone and heart rate (e.g., Hastings et al., 2008).
3. The effects of acoustic interventions (e.g., the Safe and Sound Protocol) on emotion regulation and functional neurological disorders (e.g., Heilman et al., 2023; Porges et al., 2013, 2014; Rajabalee et al. 2022).
4. The utility of autonomic state as an intervening variable − serving as a mediating factor linking environmental cues to behavioral outcomes − in psychophysiological (Dale et al., 2022), survey research (Kolacz et al., 2020), medical treatments (Donchin et al., 1992; Kovacic et al. 2020).

These predictions have been tested and supported across domains as varied as trauma studies, developmental psychobiology, and behavioral neuroscience, attesting to both the theory's falsifiability and its wide applicability. Falsifiability remains a core tenet of scientific theory, and Polyvagal Theory meets this criterion. Studies have repeatedly confirmed the theory's claims regarding autonomic flexibility, neuroception, and social engagement.

Crucially, this predictive and explanatory power extends beyond research settings into clinical practice. The theory's clinical relevance is further validated by interventions like the Safe and Sound Protocol (Heilman et al., 2023), which modulate the ventral vagal pathway and yield measurable improvements in regulation and social behavior. These predictive capacities make Polyvagal Theory not only scientifically rigorous but also instrumental in guiding, via reliable biomarkers, individualized intervention strategies − particularly in trauma-informed and neurodevelopmental care settings.

This integration facilitates hypothesis-driven research and supports informed therapeutic decisions across developmental, psychiatric, and somatic domains. By rooting its conceptual framework in neurophysiology and evolutionary biology, Polyvagal Theory maintains both scientific integrity and translational relevance, serving as a robust model for research and a practical guide for clinical care.

3. Clinical applications across disciplines

Building on these neurophysiological and translational insights, Polyvagal Theory provides a new framework for understanding and addressing clinical challenges across disciplines.

3.1 A polyvagal reorientation for clinical practice and research

Polyvagal Theory reconceptualizes psychological and behavioral symptoms as adaptive expressions of autonomic state, rather than as evidence of cognitive or emotional failure (Porges, 2022; Kolacz et al., 2019). From this perspective, many symptoms represent the nervous system's response to neurophysiological cues of threat − often occurring beneath conscious awareness. This leads to a foundational clinical question: *What autonomic state is this individual experiencing, and how can pathways to safety and connection be restored?*

Rather than targeting symptoms in isolation, Polyvagal-informed care prioritizes interventions aligned with the client's current physiological state. By recognizing state-dependent functioning, clinicians can select strategies that match an individual's physiological readiness for regulation, social engagement, and learning. This state-aware approach supports sustainable change by leveraging, rather than opposing, the body's adaptive responses.

Polyvagal Theory also generates testable predictions, linking autonomic regulation to behavioral outcomes and intervention efficacy. Objective biomarkers − including RSA, vagal efficiency, and weighted coherence − provide quantifiable indices of regulatory capacity and clinical progress (Hage et al., 2017; Kolacz et al., 2025; Porges, 2024). These measures bridge neuroscience and clinical science, transforming subjective experiences into empirically trackable data.

Across trauma, neurodevelopmental, affective, and functional domains, Polyvagal Theory offers a biologically grounded framework for guiding recovery. The following sections examine its application by clinical domain, illustrating how common autonomic mechanisms underlie diverse presentations and inform individualized pathways to regulation and connection.

Central to these processes is the construct of neuroception − the nervous system's implicit detection of safety or danger − and the VVC, a mammalian adaptation coordinating facial expression, vocal prosody, and cardiorespiratory function. When neuroception is biased toward threat, access to the VVC is compromised, constraining the capacity for calm, connection, and self-regulation. Understanding and supporting these neural systems is foundational to Polyvagal-informed care.

3.2 Trauma and mental health: autonomic pathways to recovery

Trauma induces persistent changes in the nervous system, often resulting in chronic autonomic dysregulation. Individuals exposed to trauma may remain physiologically anchored in defensive states, even in the absence of current threat. Such chronic autonomic activation can manifest as hypervigilance, dissociation, anxiety, depression, or a range of somatic symptoms.

Polyvagal Theory reframes these presentations not as psychopathology, but as adaptive responses to disrupted neuroception and restricted access to the VVC. When neuroception is tuned toward danger, the physiological pathways necessary for calm, relational engagement, and self-regulation become inaccessible. As a result, flexible movement between autonomic states is lost, and individuals may oscillate between sympathetic mobilization and dorsal vagal shutdown without reliable access to the VVC.

This pattern underlies clinical conditions such as post-traumatic stress disorder (PTSD), generalized anxiety disorder, depression, and borderline personality disorder, in which chronic dysregulation of the autonomic nervous system impedes recovery and adaptation.

Recent research highlights the critical role of vagal tone − measured by RSA and vagal efficiency − as an indicator of autonomic flexibility. Lower vagal tone is associated with decreased emotional resilience and heightened stress sensitivity (Hage et al., 2017), whereas higher tone predicts better self-regulation, social engagement, and physiological recovery. Reduced vagal efficiency has emerged as a sensitive marker of dysautonomia and functional disorders (Kolacz et al., 2019; Porges, 2024).

Interventions that shift state

Polyvagal-informed interventions focus on restoring access to the VVC and supporting adaptive shifts in autonomic state. These bottom-up approaches include:

- Acoustic protocols (e.g., Sonocea's Rest and Restore Protocol, Safe and Sound Protocol), which use modulated sound to engage the social engagement system and signal safety.
- Breath- and rhythm-based practices, such as paced breathing and vocal toning, which stimulate vagal afferents and promote parasympathetic activity.
- Biofeedback and vagus nerve stimulation (VNS), designed to enhance interoceptive awareness and autonomic regulation.
- Somatic and relational therapies, providing cues of safety through movement, touch, and co-regulation.

When tailored to an individual's physiological state, these interventions can disrupt chronic defensive patterns, restore relational capacity, and foster resilience and post-traumatic growth.

3.3 Chronic conditions and functional disorders

A growing body of evidence indicates that many chronic conditions − including irri bowel syndrome (IBS), fibromyalgia, chronic fatigue syndrome (CFS), and functional neurological disorders − are best understood as manifestations of persistent autonomic dysregulation, rather than unexplained or psychosomatic illness. Although these conditions present with disabling symptoms in the absence of clear structural pathology, research now implicates chronic disruptions in neuroception and vagal regulation as central mechanisms (Kolacz & Porges, 2018; Rajabalee et al., 2022).

From a Polyvagal perspective, such conditions are physiological consequences of a nervous system chronically biased toward defensive states. Impaired neuroception and reduced vagal efficiency disrupt the dynamic regulation of gastrointestinal, immune, pain, and metabolic systems − not due to tissue damage, but because the autonomic nervous system remains locked in states of protection.

A hallmark of these populations is low vagal efficiency − a disruption in the coupling between RSA and heart rate. This inefficiency diminishes the impact of parasympathetic tone, undermining the body's ability to recover, restore energy, and maintain homeostasis and has been related to disorder associated with dysautonomia such as hypermobility syndrome (Kolacz et al., 2021), cyclic vomiting syndrome (Kolacz et al., 2022). In addition, auricular vagal nerve stimulation has increased vagal efficiency, while reducing pain symptoms (Kolacz et al. 2025).

Despite the diversity of symptoms, many chronic conditions share common underlying autonomic patterns. As outlined in **table 2**, these mechanisms − such as reduced vagal inhibition of sympathetic tone and impaired modulation of inflammation and pain − contribute to the breadth of clinical presentations observed across functional disorders. Notably, these symptoms are not imagined or exaggerated; rather, they represent deeply embodied responses to an autonomic system unable to shift out of chronic threat. In functional GI disorders, for example, autonomic disruption is often compounded by comorbidities such as joint hypermobility, reflecting a broader systemic pattern of dysregulation (Kolacz et al., 2021).

Pathways to regulation

Polyvagal-informed care aims to restore autonomic flexibility and enhance vagal function. Clinicians employ a range of bottom-up, state-shifting interventions − summarized in **table 3** − that support parasympathetic tone, recalibrate neuroception, and promote recovery through safety signaling.

When interventions are matched to an individual's physiological state, they can interrupt chronic defense patterns, restore access to the VVC, and support the regulation of subdiaphragmatic systems. In this way, Polyvagal-informed care provides a pathway to symptom resolution through the restoration of physiological safety, rather than through symptom suppression alone (Porges, 2022).

These symptoms are not imagined or exaggerated − they reflect deeply embodied, neurophysiological responses to an autonomic system unable to downshift from threat. For example, autonomic disruption in functional GI disorders is often compounded by comorbidities such as joint hypermobility, highlighting a systemic pattern of dysregulation (Kolacz et al., 2021). Such systemic dysregulation reinforces the Polyvagal perspective that chronic functional symptoms often reflect hierarchical and integrated disruptions across the autonomic network.

3.4. Developmental and attachment contexts

The early development of autonomic regulation is fundamentally shaped through relational co-regulation between infants and caregivers. From a Polyvagal perspective, attachment is not merely an emotional or cognitive construct − it is a neurophysiological process rooted in the calibration of the autonomic nervous system through social interaction.

When caregivers are responsive, periodic, and attuned, their own regulated states serve as anchors, helping to establish vagal flexibility in the infant. This facilitates the child's ability to shift flexibly between physiological states and to build emotional resilience. Such co-regulatory interactions create the biological foundation for later self-regulation, social engagement, and cognitive growth.

Conversely, early adversity − including neglect, trauma, or inconsistent caregiving − can bias neuroception toward threat, reducing access to the VVC. Children exposed to these disruptions often display emotional lability, behavioral dysregulation, attention difficulties, or social withdrawal. These behaviors are not signs of willful misbehavior or cognitive deficit, but rather expressions of a nervous system that remains chronically locked in defense.

Implications for practice

Polyvagal-informed developmental interventions focus on restoring physiological safety through structured, relationally attuned environments. As outlined in **table 3**, effective strategies include:

- Trauma-informed educational practices that emphasize rhythm, predictability, and relational safety.
- Co-regulation techniques within caregiver–child interactions that build tolerance for autonomic shifts.
- Developmentally appropriate mindfulness and movement, which support interoception and promote vagal tone.

Table 2. *Mechanisms and clinical features*

Condition	Autonomic Pattern	Mechanism	Common Symptoms
IBS / Gut disorders	Chronic or alternating sympathetic or dorsal vagal tone	Inhibited GI motility	Bloating, discomfort, irregular bowel patterns
Fibromyalgia / Chronic Pain	Persistent sympathetic tone	Loss of vagal inhibition of sympathetic activity promotes musculoskeletal pain	Widespread pain, fatigue, heightened sensitivity
Functional Neurological	Defensive immobilization (shutdown)	Altered neuroception of threat	Motor/sensory disruption without structural cause
Chronic Fatigue Syndrome	Low vagal efficiency	Energy conservation in defense state	Exhaustion, exertion intolerance

Practical tools such as rhythmic pacing, prosodic voice, relational presence, and consistent routines directly stabilize autonomic state and help recalibrate neuroception, thereby allowing children to access higher-order cognitive and social capacities.

Longitudinal research demonstrates that early vagal tone predicts later emotional regulation and social competence (Calkins & Keane, 2004; Porges et al., 1996). Thus, supporting caregiver self-regulation is not only critical for the child's immediate development – it plays a key role in breaking intergenerational cycles of dysregulation.

3.5 Lifespan and systems of care

The foundational role of autonomic regulation extends across the lifespan, shaping health, resilience, and relational well-being at every stage of development. Building on the early caregiving dynamics described in the previous section, Polyvagal Theory provides a framework for understanding how physiological regulation underlies adaptive functioning – from infancy through older adulthood – and is influenced by the systems and environments in which individuals are embedded.

Developmentally tuned care

In neonatal and pediatric care, Polyvagal-informed protocols recognize that medical stabilization alone is insufficient; environments that reliably cue safety are essential. Practices such as skin-to-skin contact, rhythmic rocking, and prosodic vocalization engage the social engagement system and foster early co-regulation between infants and caregivers. These strategies promote healthy vagal development and influence long-term emotional and physiological outcomes.

In early childhood and educational settings, the use of consistent relational cues, predictable routines, and embodied safety signals scaffolds the maturation of vagal flexibility and emotional self-regulation. Such environmental attunement establishes a foundation for learning, cooperation, and well-being.

Aging and autonomic decline

As individuals age, there is a natural decline in vagal tone (Byrne et al., 1996), associated with increased systemic inflammation, reduced heart rate variability, and diminished recovery capacity. These physiological changes can impair emotional regulation, exacerbate chronic illness, and contribute to cognitive decline.

Interventions that preserve or enhance vagal flexibility – such as movement, breath-based practices, acoustic stimulation, and social connection – buffer against age-related autonomic rigidity. As described in **table 3**, these approaches support resilience and sustain engagement even in the presence of physical or cognitive challenges.

In palliative and hospice care, the presence of attuned caregivers – those who offer safety through tone, touch, and relational presence – can activate VVC pathways. Even when verbal communication is limited, these embodied signals foster dignity, connection, and comfort at the end of life.

System-level implications

The environments of care – whether hospitals, schools, or long-term care facilities – shape neuroception and thus directly influence autonomic state. Elements such as lighting, soundscapes, predictability, relational dynamics, and institutional rhythms all contribute to the implicit cues of safety or threat experienced by those within the system.

Polyvagal-informed systems prioritize bottom-up regulation over top-down control, recognizing that healing, learning, and engagement arise not from external demand, but from the restoration of physiological safety. When institutions intentionally promote co-regulation, rhythm, and relational presence, they create environments conducive to regulation and resilience across all stages of life.

This systems-level perspective sets the stage for understanding how stress, adversity, and chronic dysregulation can disrupt health across the lifespan – a theme explored in the following section.

3.6 Stress and autonomic regulation

Building on the systems-level perspective established in the previous section, Polyvagal Theory offers a transformative reframing of stress – not as a

Table 3. *Polyvagal-informed interventions and mechanisms*

Intervention	Mechanism	Function
Sonic Augmentation Technology *(e.g., Sonocea's Rest and Restore Protocol)*	Rhythmic acoustic modulation mirrors endogenous autonomic rhythms and signals brainstem centers	Supports co-regulation, visceral homeostasis, and immobilization without fear
Safe and Sound Protocol (SSP)	Prosodic auditory stimulation activates middle ear muscles and VVC pathways	Enhances social engagement readiness and shifts neuroception toward safety
Breath- and Rhythm-Based Practices *(e.g., slow-paced breathing, vocal toning)*	Stimulates vagal afferents and supports parasympathetic dominance	Improves regulation, interoceptive awareness, and emotional balance
HRV Biofeedback & Coherence Training	Trains awareness of vagal tone via real-time feedback on RSA and heart rate	Increases vagal and self-regulatory capacity
Vagus Nerve Stimulation (VNS)	Auricular taVNS, Cervical tcVNS	Augments parasympathetic tone and supports autonomic flexibility
Somatic and Relational Therapies *(e.g., touch, co-regulation, movement)*	Provide bottom-up cues of safety through embodied presence and rhythm	Reinforces safety signaling, facilitates state transitions, and supports relational engagement

solely psychological or environmental phenomenon, but as a disruption in autonomic regulation rooted in neurophysiological state. Stress is thus best understood not simply as what happens to us, but as how the nervous system detects, interprets, and recovers from challenge.

From an evolutionary standpoint, stress responses are adaptive: sympathetic mobilization and dorsal vagal immobilization are critical for survival in the face of threat. However, when neuroception is persistently biased toward danger – even in the absence of an external challenge – the body can become locked in defensive autonomic states. This chronic autonomic rigidity impairs physiological recovery and contributes to symptoms such as cardiovascular strain, inflammation, digestive disturbance, and emotional dysregulation.

The central role of the ventral vagal complex (VVC)

At the heart of adaptive stress regulation is the VVC. When functioning optimally, the VVC inhibits defensive reflexes, supports calm engagement, and allows for flexible transitions between arousal and restoration. Compromised VVC function – due to trauma, adversity, or cumulative stress – undermines this flexibility, resulting in allostatic overload and increased vulnerability to both physical and mental health challenges.

Interventions that restore regulation

Polyvagal-informed interventions aim to restore physiological flexibility by supporting VVC dominance and enabling spontaneous shifts from defense to safety. As detailed in **table 3**, strategies include:

- Breathwork and mindfulness practices that engage interoception and slow vagal rhythms.
- Somatic and trauma-informed movement to re-establish coherence between body and autonomic state.
- Acoustic stimulation protocols (e.g., the Safe and Sound Protocol) to enhance vagal tone through prosodic auditory input.
- Co-regulation with others, using relational safety cues to facilitate neuroceptive shifts.

In this framework, resilience is redefined – not as the mere absence of stress, but as the capacity to shift autonomic state and recover. True resilience reflects not willpower, but the adaptive flexibility of a well-regulated nervous system that can access calm, connection, and restoration even in the face of adversity. This understanding of stress as a disruption of homeostatic regulation sets the stage for exploring how psychotherapy and trauma recovery can be optimized by targeting state regulation – a theme developed in the next section.

3.7 Psychotherapy and trauma recovery

Building upon the recognition that stress reflects disruptions in autonomic regulation, Polyvagal Theory offers a transformative lens for psychotherapy – one that places physiological state at the heart of healing. Traditional approaches may focus on thoughts and emotions, but Polyvagal-informed therapy begins with the body: many symptoms that bring clients to treatment – hypervigilance, numbing, dissociation, intrusive memories – originate in persistent defensive autonomic states, maintained by disrupted neuroception.

In trauma survivors, this defensive neuroception often remains active even in safe environments, limiting access to the VVC and impeding relational engagement, self-reflection, and emotional integration. Within this framework, dysregulation is understood not as a failure of effort or insight, but as a survival adaptation – a physiological legacy of past threat.

The core role of the therapeutic relationship

A central insight of Polyvagal-informed therapy is that the therapist's own nervous system becomes a powerful regulatory tool. Through prosodic voice, expressive face, and attuned pacing, the therapist offers nonverbal cues of safety, actively engaging the client's VVC and inviting physiological calm. Here, safety is not merely a topic of conversation; it is embodied and transmitted.

Rather than expecting clients to regulate while dysregulated, Polyvagal-guided interventions prioritize the creation of regulatory conditions – shifting state before engaging cognitive or narrative processes. When the VVC is accessible, the nervous system exits defense, allowing space for connection, emotional flexibility, and deeper trauma processing.

Polyvagal-informed therapeutic strategies

Effective therapy, from this perspective, is sequenced: state awareness and bottom-up regulation come first, followed by cognitive and narrative integration. Interventions such as those outlined in Section 3.3 (Pathways to Regulation), Section 3.6 (Interventions That Restore Regulation), and detailed in **table 3,** provide clinicians with tools to facilitate this critical shift toward safety and co-regulation. For example, integrative approaches such as Polyvagal-Informed EMDR (Kase, 2023) blend bilateral stimulation with co-regulatory strategies, specifically engaging the VVC before memory processing to reduce retraumatization and optimize integration.

Importantly, therapist self-regulation is not an optional skill, but a foundational necessity. A dysregulated therapist can unwittingly reinforce a client's neuroception of danger. By contrast, a calm, attuned presence anchors the therapeutic environment, enabling clients to feel both heard and physiologically safe. In sum, Polyvagal Theory reframes trauma recovery as a process grounded in physiological state access. Healing unfolds not simply through retelling the story, but by cultivating the internal conditions – through breath, body, and relationship – in which genuine transformation is possible**.** This body-based orientation extends beyond individual therapy, informing new approaches to education, organizational systems, and community design – topics explored in the following section.

3.8 Translational implications: education, organizations, and communities

Polyvagal Theory extends well beyond clinical care to provide a unifying framework for shaping environments that support physiological regulation, relational engagement, and co-regulation at all levels of society. Whether in schools, workplaces, neighborhoods, or civic institutions, neuroception – the nervous system's implicit detection of safety or danger – profoundly shapes how people behave, relate, and learn.

The power of context: safety and threat

When environments consistently cue safety, individuals are able to access ventral vagal states that support trust, cooperation, curiosity, and learning. In contrast, environments that cue danger – through unpredictability, exclusion, harsh tone, or sensory overload – tend to promote defensive autonomic states. These shifts in state are often misinterpreted as poor behavior, disengagement, or lack of motivation, when in reality, they are adaptive physiological responses to context.

Education: learning requires safety

Learning is fundamentally state-dependent. Cognitive, emotional, and social development are only possible when the nervous system is regulated. Chronic stress, early adversity, or neurodevelopmental differences can bias neuroception toward threat, undermining attention, self-regulation, and connection.

Polyvagal-informed educational practices emphasize predictability, rhythm, and relational attunement, including:

- Predictable routines and relationally anchored transitions
- Prosodic, regulated voice tone from educators
- Opportunities for movement and rhythm to facilitate state shifts
- Micro-regulation practices (e.g., breathwork, mindfulness, co-regulation breaks)

In these settings, the educator's nervous system functions as a co-regulatory anchor. When teachers embody calm and presence, students experience implicit physiological safety through relational synchrony.

Organizations: nervous systems at work

Workplaces typically prioritize performance and productivity, often overlooking the autonomic states that support or inhibit collaboration and innovation. Environments characterized by hierarchical threat, unpredictability, or exclusion may chronically activate defensive states, diminishing creativity and resilience.

Polyvagal-informed organizational practices include:

- Promoting psychological safety through congruent communication
- Leadership training grounded in nervous system science
- Structured rhythms that support reflection and regulation
- Feedback and conflict resolution rooted in attunement and empathy

Such approaches foster collective regulation and sustainable creativity, allowing both individuals and teams to flourish.

Communities: designing for collective safety

At the community level, structural adversity – including racism, poverty, and violence – disrupts neuroception on a population scale, locking individuals and groups into chronic defensive states. Polyvagal-informed community interventions emphasize bottom-up safety through rhythm, ritual, and relational repair, such as:

- Restorative justice circles and participatory storytelling
- Embodied group rituals that promote co-regulation
- Trauma-informed public space design (e.g., periodic sound, light, and layout)
- Leadership development focused on presence, regulation, and relational coherence

These interventions shift the paradigm of healing from targeting individual dysfunction to supporting collective state change.

Polyvagal Theory reframes the guiding question for environmental design: Does this environment send cues of safety that invite engagement, connection, and regulation – or does it convey cues of danger?

Rooted in Polyvagal Theory, this guiding question offers a compass for designing systems and communities in which nervous systems – and relationships – can truly thrive.

3.9 Summary and future directions

Polyvagal Theory provides a biologically grounded, integrative framework for understanding human behavior, health, and relational capacity. By anchoring symptoms and responses in autonomic state, the theory reframes pathology not as dysfunction, but as an adaptive strategy − reflecting how the nervous system detects and responds to cues of safety or threat. Across trauma recovery, functional health, development, education, psychotherapy, organizational behavior, and public systems, a consistent principle emerges - Autonomic safety is the prerequisite for regulation, resilience, and connection.

Key contributions of a polyvagal framework:

- Reframes symptoms as state-dependent autonomic responses.
- Highlights co-regulation as a biological necessity.
- Introduces measurable physiological indices (e.g., RSA, vagal efficiency, weighted coherence).
- Informs bottom-up interventions grounded in state awareness and physiological state change.
- Provides a neurophysiological lens to evaluate environments, systems, and institutions.

As Polyvagal Theory continues to evolve into a translational paradigm, new opportunities are emerging across disciplines. While the theoretical model and clinical applications are well-supported, ongoing empirical testing − especially in diverse populations and naturalistic settings − will further refine its scope and impact.

Emerging frontiers include:

- Scalable interventions in healthcare, education, and community practice.
- Wearable technologies for real-time state monitoring and vagal engagement.
- Early caregiving research, including NICU regulation and attachment repair.
- Cross-cultural applications, integrating ancestral and embodied practices.
- Policy and environmental design that prioritize rhythm, predictability, and inclusivity.

This future is not only scientific, but ethical. As Polyvagal Theory shifts from abstract model to actionable framework, it challenges institutions and communities to prioritize physiological safety and co-regulation. When these principles are embedded into systems, they become engines of transformation and repair.

Regulation precedes learning. Safety enables creativity. Healing begins not with cognition − but with connection. This summary and future vision set the stage for methodological innovations in autonomic science, explored in the next section.

4. Methodological innovation and autonomic metrics

Building on the foundational science and translational opportunities outlined above, methodological advances are enabling a more nuanced and actionable understanding of autonomic regulation. Moving beyond traditional amplitude-based measures of RSA, contemporary autonomic science increasingly leverages multidimensional metrics that align with the systems-level integration at the core of Polyvagal Theory.

4.1 Beyond RSA: new metrics for autonomic function

While RSA amplitude has long served as a robust, noninvasive index of cardiac vagal tone, amplitude alone does not capture the dynamic coordination between brainstem structures and peripheral effectors that define healthy autonomic regulation. Recent innovations have produced complementary metrics that reveal functional coupling, efficiency, and synchrony within the autonomic system.

Expanding the toolkit: two complementary metrics

1. Vagal Efficiency measures the relationship between RSA and heart rate across time. It reflects the effectiveness with which respiratory-linked vagal activity modulates heart rate. Low VE suggests that while vagal signals may be present (as indexed by RSA), they are not producing expected downstream effects − indicating impaired central–peripheral integration (Porges, 2024). Impaired vagal efficiency has not only been related to adversity history (Dale et al., 2022) but has been observed in adolescents with functional gastrointestinal disorder, hypermobility syndrome, as well as predicting treatment responsiveness to chronic gastrointestinal pain (Kolacz et al., 2021; Kolacz et al., 2022; Kovacic et al., 2020).
2. **Weighted Coherence** quantifies the synchrony between respiratory and cardiac rhythms in the frequency domain (Porges et al., 1980). This dynamic index captures subtle shifts in coordination that may signal transitions between autonomic states. Thus, although the respiratory pattern in heart rate (i.e., RSA) may be high, it may not be coupled with the respiratory pattern of inhalation being phase-locked with heart rate increases and exhalation being phase-locked with heart rate deceleration. For example, declining weighted coherence may reflect a brainstem process that would anticipate dysregulation before overt behavioral or health signs emerge.

The integration of multiple autonomic metrics − capturing amplitude, coupling, and timing − enables a multidimensional characterization of vagal regulation. Combined, these measures advance assessment beyond static indices, facilitating a dynamic, systems-level understanding of autonomic function. This approach supports the development of tailored intervention strategies and the sensitive monitoring of therapeutic progress, particularly in populations affected by trauma, neurodevelopmental conditions, and functional disorders.

4.2 Wearables and real-time monitoring

The emergence of wearable biosensors marks a turning point in autonomic science. By continuously capturing ECG, respiration, and movement, wearables enable real-time assessment of nervous system function in naturalistic contexts − including therapy sessions, interpersonal interactions, sleep, and daily life.

Polyvagal-Informed Applications:

- Provide real-time feedback during moments of

dysregulation, prompting self-regulation strategies.
- Detect stress-inducing environments using context-aware algorithms.
- Enhance trauma-informed care, particularly in individuals with physiologically masked states.
- Support therapeutic alliance with shared data across sessions.

Clinical Examples:

- Neonatal intensive care interventions interventions that use vagal efficiency and RSA metrics to guide autonomic maturation and promote caregiver–infant bonding (Porges et al., 2019).
- Somatic therapy utilizing coherence drops to signal readiness for intervention.
- Remote care teams tracking recovery and autonomic stability in dysautonomia or long COVID.

Ethical considerations:

While wearable technology expands access and insight, its use must be guided by strong ethical safeguards: privacy, informed consent, and respect for autonomy. Physiological data are powerful but must be carefully stewarded, particularly in sensitive settings. These advances support not only individual care, but also scalable approaches to group interventions and public health.

4.3 Translational applications in clinical practice

The clinical utility of polyvagal-informed metrics – such as RSA, vagal efficiency (VE), and weighted coherence – lies in their ability to make autonomic state visible, interpretable, and actionable. These tools extend the therapeutic conversation beyond symptoms and narratives to include the physiological rhythms that underlie regulation, resilience, and relational engagement.

From symptom checklists to physiological storytelling

In trauma-informed psychotherapy, traditional models often rely on verbal processing or client self-report. Yet many trauma survivors remain disconnected from their internal state or unable to verbally articulate distress. Physiological metrics offer a nonverbal map of state shifts that can be integrated into treatment.

For example:

- Monitoring RSA and vagal efficiency may help clinicians determine whether a client is in a neurophysiological state that supports memory reconsolidation or emotional processing.
- Tracking RSA across sessions provides an index of the client's baseline regulation capacity and response to interventions over time.

This bio-informed dialogue fosters physiological insight – what some clinicians call "body storytelling." Clients begin to recognize patterns of reactivity, recovery, and relational vulnerability through data-informed reflection, enhancing both agency and engagement.

Examples of application

- In neonatal intensive care unit settings, RSA and vagal efficiency metrics guide interventions aimed at autonomic maturation and caregiver–infant bonding (Porges et al., 2019). This supports the early emergence of vagal tone and co-regulation capacity in preterm infants.
- In somatic therapy, a drop in RSA may signal that a client is approaching a defensive state, prompting the therapist to pause, co-regulate, or shift strategy before overwhelm occurs.
- Neuromodulation using computer-altered music (e.g., Safe & Sound Protocol) has been effective even in pediatric cases of functional neurological disorders unresponsive to standard interventions – underscoring the power of acoustic cues to shift state and restore regulatory capacity (Rajabalee et al., 2022).
- In group therapy, real-time feedback from wearable sensors can help participants understand how relational dynamics affect physiological safety, deepening insight and accountability.

Expanding access and equity

Polyvagal-informed metrics also support inclusivity in care. Because they do not rely on verbal articulation, they offer meaningful access points for:

- Nonverbal or minimally verbal individuals, including autistic clients or preverbal infants.
- Neurodiverse populations who process and express affect differently.
- Clients from culturally diverse backgrounds, where distress may be communicated through bodily or relational cues rather than explicit language.

By centering the nervous system as narrator, clinicians can attune to suffering that might otherwise be overlooked or misinterpreted. As these new tools proliferate, the field faces both exciting opportunities and new challenges – requiring rigorous research, ethical vigilance, and a commitment to science as a tool for healing, not just classification.

4.4 Future directions in autonomic science

The evolution of Polyvagal Theory has catalyzed a new generation of physiologically grounded, ethically informed, and translationally relevant tools for understanding human experience. As these innovations mature, future research and implementation efforts will need to balance technical rigor with clinical nuance, and scalability with individualized care.

Key frontiers for research and development

1. **Defining normative ranges without overpathologizing difference**
   While autonomic metrics hold diagnostic potential, normative values must reflect developmental, cultural, and contextual variation. Researchers must resist the temptation to define fixed thresholds for "healthy" regulation that ignore natural diversity or impose dominant cultural frameworks.
2. **Multimodal integration of bio-social signals**
   Next-generation research will integrate autonomic data with complementary systems:
   - Neuroimaging to link brainstem-autonomic coordination with cortical processing
   - Voice acoustics to index vagal tone through prosody and vocal control
   - Facial expressivity using computer vision to track engagement cues and micro-shifts in

neuroception

These data streams converge on a holistic picture of state regulation in both individuals and social systems.

3. **Training the next generation of clinicians and scientists**
   As autonomic monitoring becomes more accessible, training programs must equip professionals to interpret these data accurately and ethically. Misapplication or overinterpretation can undermine trust, reinforce bias, or flatten complexity into one-size-fits-all protocols.

A science of connection, not just classification

The goal of polyvagal-informed autonomic science is not merely to refine measurement − it is to deepen our understanding of the body's capacity for safety, engagement, and repair. These metrics should not be used to classify people, but to empower them: making invisible physiological patterns understandable, trackable, and changeable. Methodological innovation becomes transformative when it helps people see themselves − and one another − through a lens of nervous system possibility rather than pathology. As Polyvagal-informed science advances, its success will be measured not only by accuracy, but by its capacity to support compassionate, embodied care across clinical, educational, and communal settings.

5. Polyvagal-informed systems and institutional design

Polyvagal Theory offers more than a neurobiological model of individual behavior; it provides a transformational framework for designing institutions that foster safety, connection, and resilience. Whether in healthcare, education, justice, or community systems, one principle prevails: **physiology precedes behavior**. Institutions that respect the nervous system's imperative for safety create environments where regulation, engagement, and growth become possible.

Institutions often fall short not due to resource scarcity or policy flaws, but because they neglect the autonomic needs of those they serve. A school that punishes dysregulation, a hospital that delivers alienating care, or a courtroom that mistakes immobility for defiance − all reflect systems misaligned with human neurobiology. By re-examining environments through the lens of Polyvagal Theory, we can move from systems that reinforce defense and disengagement to ones that reliably cue safety and support regulation.

Polyvagal Theory reframes the central question for institutional design:

Does this environment send cues of safety or cues of danger?

When systems chronically evoke neuroceptive threat − through unpredictability, harsh tone, isolation, or sensory overwhelm − they entrench defensive states. In contrast, systems intentionally designed to support dynamic co-regulation. reliably cue safety and connection, fostering resilience at scale.

5.1 Rethinking institutions through a polyvagal lens

Viewing institutions through a polyvagal lens invites a profound redesign. It challenges us to move beyond retrofitting wellness initiatives onto existing frameworks. Instead, the nervous system itself must be treated as a **design constraint** − a biological blueprint that shapes structural, relational, and procedural choices from the ground up.

Institutions that design *with* rather than *against* human physiology can:

- Stabilize autonomic state
- Facilitate real-time co-regulation
- Unlock capacities for reflection, creativity, and mutual care

Rather than asking whether a policy "works," polyvagal-informed design asks whether it **stabilizes autonomic regulation and supports access to the social engagement system**.

5.2 Design principles for polyvagal-informed systems

Decades of research distill into actionable design principles that foster safety and autonomic resilience. These elements are not optional extras; they are **neurobiological imperatives**, especially for individuals shaped by adversity.

Each design element in **table 4** shapes *how* systems feel, not just how they function. By embedding these principles into daily operations, institutions can transform from neutral − or even threatening − spaces into active supports for resilience and engagement.

5.3 From trauma-informed to autonomic-aware

Trauma-informed approaches emphasize understanding the impact of past adversity. Polyvagal-informed systems extend this focus by emphasizing real-time **autonomic state**: not only *what happened*, but *what is happening now* in the body. Autonomic-aware systems prioritize shifting physiological state, not merely increasing insight. This requires:

- **Training staff** to recognize and respond to autonomic cues with co-regulation strategies.
- **Using state-informed metrics** (e.g., RSA, Vagal Efficiency) to tailor interventions and monitor regulation.
- **Designing policies** that proactively reduce threat and build rhythmic, regulatory environments.

By focusing on **present-moment physiology**, these systems enable dynamic support for regulation, connection, and recovery across settings.

5.4 Translating polyvagal insights into policy and practice

Building polyvagal-informed systems demands an integration of **neurobiological literacy, relational attunement, and environmental design**. This translational work requires interdisciplinary collaboration among neuroscientists, clinicians, educators, designers, and policy architects.

Practical applications include:

- **Schools**: Embedding co-regulation into pedagogy, classroom rhythms, and discipline practices.
- **Healthcare**: Designing relationally safe intake, treatment, and discharge protocols that buffer threat and promote stabilization.

- **Justice Systems**: Applying trauma-informed, neurobiologically respectful practices that recognize autonomic states underlying behavior.
- **Community Organizations**: Structuring spaces and programs around rhythmicity, predictability, and relational safety to buffer chronic threat detection.

When Polyvagal principles inform system-wide policy, they cultivate environments that nourish rather than deplete human potential.

5.5 The Nervous System as a Design Constraint

Polyvagal Theory ultimately proposes a design revolution: **Human physiology must be treated as a foundational constraint in institutional design, not an afterthought.** Polyvagal-informed institutions do not retrofit wellness initiatives onto traditional systems. Instead, they:

- Begin with the nervous system's architecture
- Build outward from principles of autonomic safety
- Align every structural, relational, and procedural decision with the body's biological needs for predictability, co-regulation, and participation

When we design *for* the nervous system, we move beyond symptom reduction. We **unlock the full potential** of regulation, reflection, creativity, connection, and healing.

This paradigm prepares us to consider the broader scientific, ethical, and translational implications of Polyvagal Theory − a journey addressed in the concluding section.

6. Conclusion: polyvagal theory − from biological bedrock to systemic change

Polyvagal Theory offers a transformative, biologically anchored framework for understanding human behavior, health, and relational capacity. At its core is the recognition that beneath emotion, cognition, and action lies a hierarchical autonomic architecture − shaped by evolutionary adaptation, molecular innovation, and the demands of mammalian sociality.

Bedrock empirical foundations

The validity of Polyvagal Theory rests on convergent evidence from comparative anatomy, neurophysiology, biobehavioral research, and transcriptomics:

- **Anatomical Innovation:** The mammalian VVC emerged through the ventral migration and myelination of cardioinhibitory vagal fibers into the NAmb, enabling a structural platform for attachment, prosody, and coregulation.
- **Neurophysiological Distinction:** The VVC, supported by a mammalian-specific brainstem oscillator, enables rapid, context-sensitive modulation of cardiac output − indexed by RSA − and supports state shifts fundamental to social engagement and resilience.
- **Behavioral and Biobehavioral Expression:** Only mammals display the full spectrum of social engagement behaviors − facial expressivity, vocal prosody, reciprocal touch, and synchrony − which foster resilience and relational health. Disruption of ventral vagal function is linked to clinical syndromes such as trauma and autism, while robust vagal regulation predicts adaptive capacity.
- **Transcriptomic Confirmation:** Recent analyses reveal that the mammalian NAmb expresses a suite of genes supporting myelination (e.g., Mbp, Myrf), synaptic integration (Snap25), and neuropeptide signaling (oxytocin, vasopressin receptors) − molecular signatures absent or minimal in non-mammalian vertebrates. These specializations enable rapid, nuanced social regulation and mark a true evolutionary divergence.

Key innovations and testable constructs

By synthesizing these lines of evidence, Polyvagal Theory establishes a set of actionable constructs and operational innovations:

- **Dissolution:** The Jacksonian principle that under threat, the autonomic nervous system sequentially expresses defensive states in reverse phylogenetic order.
- **Autonomic State as Intervening Variable:** PVT operationalizes autonomic state − objectively indexed by physiological markers (RSA, vagal efficiency, weighted coherence) − as a measurable mediator of health, behavior, and intervention outcomes.
- **The Social Engagement System:** The coordinated activity of cranial nerves V, VII, IX, X, and XI forms the VVC, anatomically and functionally underpinning mammalian sociality, reciprocal signaling, and coregulation.
- **Neuroception:** The nervous system's non-conscious detection of safety or threat, initiating adaptive shifts in autonomic state and influencing vulnerability or resilience.
- **Redefining Stress:** Stress is reframed as a quantifiable disruption of homeostatic autonomic rhythms, measurable through physiologic and digital health advances.
- **Mammalian RSA and Vagal Efficiency:** RSA

Table 4. *Designing for regulation: elements that foster safety and autonomic resilience*

Design Element	Physiological Target
Predictable rhythm	Stabilizes autonomic state through structured transitions and routines
Prosodic communication	Engages the ventral vagal complex via warm tone and facial expressivity
Relational presence	Facilitates co-regulation and reduces physiological threat
Sensory safety	Minimizes auditory, visual, and tactile triggers to prevent defense
Participation & agency	Enhances autonomic flexibility by reducing powerlessness

serves as a dynamic, noninvasive index of ventral vagal activity, and vagal efficiency sensitively reflects the flexibility and resilience of the autonomic system.

Translational and Ethical Implications

Polyvagal Theory does not merely explain clinical or developmental phenomena – it provides a robust, tes framework to guide future research, interventions, and systems design. Its principles have informed the creation of acoustic interventions, wearable biomarkers, and clinical protocols that directly engage the biology of safety and connection. By honoring these foundational principles, systems and institutions are challenged to move beyond symptom management, instead fostering environments that enable regulation, co-regulation, and mutual care.

A Foundation for the Future

With these principles as its scientific bedrock, Polyvagal Theory empowers both basic science and clinical practice to rigorously test and apply its constructs – optimizing interventions and fostering a culture that honors our evolutionary need for connection. This paradigm is both scientific and ethical, advancing health, development, and compassionate connection as biological imperatives for individuals and society.

Ultimately, to be human is to need one another. The ability to feel safe – with ourselves and in the presence of others – is not a luxury, but a biological imperative. Mutual regulation forms the evolutionary foundation of healing, justice, trust, and our shared humanity. When we recognize that safety and connection are essential to well-being, we move closer to creating systems and communities that support not only survival, but the fullest expression of what it means to be human. In honoring our biological need for safety and connection, we move closer to building not only healthier individuals, but a more resilient, compassionate society.

The future illuminated by Polyvagal Theory is not merely one of survival – but one of shared vitality, healing, and hope.

References

Byrne, E. A., Fleg, J. L., Vaitkevicius, P. V., Wright, J., & Porges, S. W. (1996). Role of aerobic capacity and body mass index in the age-associated decline in heart rate variability. *Journal of Applied Physiology, 81*(2), 743–750.

Calkins, S. D., & Keane, S. P. (2004). Cardiac vagal regulation across the preschool period: Stability, continuity, and implications for childhood adjustment. *Developmental Psychobiology, 45*(3), 101–112.

Cao, Y., Wang, J., Zhang, L., & Hernandez, J. (2019). Disambiguating the nucleus ambiguus with single-cell transcriptomics. *Diabetes, 68*(Supplement 1), 582-P. https://doi.org/10.2337/db19-582-P

Dale, L. P., Kolacz, J., Mazmanyan, J., Leon, K. G., Johonnot, K., Bossemeyer Biernacki, N., & Porges, S. W. (2022). Childhood maltreatment influences autonomic regulation and mental health in college students. *Frontiers in Psychiatry, 13*, 841749.

Donchin, Y., Constantini, S., Szold, A., Byrne, E. A., & Porges, S. W. (1992). Cardiac vagal tone predicts outcome in neurosurgical patients. *Critical care medicine*, *20*(7), 942-949.

Grossman, P. (2023). Fundamental challenges and likely refutations of the five basic premises of the polyvagal theory. *Biological Psychology, 172*, 108589. https://doi.org/10.1016/j.biopsycho.2023.108589

Grossman, P., & Taylor, E. W. (2007). Toward understanding respiratory sinus arrhythmia: Relations to cardiac vagal tone, evolution and biobehavioral functions. *Biological Psychology, 74*(2), 263–285. https://doi.org/10.1016/j.biopsycho.2005.11.014

Hage, B., Sinacore, J., Heilman, K., Porges, S. W., & Halaris, A. (2017). Heart rate variability predicts treatment outcome in major depression. *Journal of Psychiatry and Brain Science, 2*(6). https://doi.org/10.20900/jpbs.20170023

Heilman, K. J., Heinrich, S., Ackermann, M., Nix, E., & Kyuchukov, H. (2023). Effects of the Safe and Sound Protocol™ (SSP) on sensory processing, digestive function and selective eating in children and adults with autism: A prospective single-arm study. *Journal on Developmental Disabilities*, *28*(1), 1-26.

Kase, R. (2023). *Polyvagal-Informed EMDR: A Neuro-Informed Approach to Healing*. WW Norton & Company.

Kolacz, J., & Porges, S. W. (2018). Chronic diffuse pain and functional gastrointestinal disorders after traumatic stress: Pathophysiology through a polyvagal perspective. *Frontiers in Medicine, 5*, 145. https://doi.org/10.3389/fmed.2018.00145

Kolacz, J., Kovacic, K. K., & Porges, S. W. (2019). Traumatic stress and the autonomic brain–gut connection in development: Polyvagal theory as an integrative framework for psychosocial and gastrointestinal pathology. *Developmental Psychobiology, 61*(5), 796–809. https://doi.org/10.1002/dev.21852

Kolacz, J., Roath, O. K., Lewis, G. F., & Karrento, K. (2025). Cardiac Vagal Efficiency Is Enhanced by Percutaneous Auricular Neurostimulation in Adolescents With Nausea: Moderation by Antidepressant Drug Exposure. *Neurogastroenterology & Motility*, e15007. VE increase only in SS without antidepressant drugs reduced nausea

Kolacz, J., Kovacic, K., Dang, L., Li, B. U., Lewis, G. F., & Porges, S. W. (2022). Cardiac vagal regulation is impeded in children with cyclic vomiting syndrome. *Official journal of the American College of Gastroenterology| ACG*, 10-14309.

Kolacz, J., Kovacic, K., Lewis, G. F., Sood, M. R., Aziz, Q., Roath, O. R., & Porges, S. W. (2021). Cardiac autonomic regulation and joint hypermobility in adolescents with functional abdominal pain disorders. *Neurogastroenterology & Motility*, *33*(12), e14165.

Kolacz, J., Dale, L. P., Nix, E. J., Roath, O. K., Lewis, G. F., & Porges, S. W. (2020). Adversity history predicts self-reported autonomic reactivity and mental health in US residents during the COVID-19 pandemic. *Frontiers in psychiatry*, *11*, 577728.

Kovacic, K., Kolacz, J., Lewis, G. F., & Porges, S. W (2020). Impaired vagal efficiency predicts auricular neurostimulation response in adolescent functional abdominal pain disorders. *The American Journal of Gastroenterology, 115*(9), 1534–1538. https://doi.org/10.14309/ajg.0000000000000763

Lewis, G. F., Furman, S. A., McCool, M. F., & Porges, S. W. (2012). Statistical strategies to quantify respiratory sinus arrhythmia: are commonly used metrics equivalent?. *Biological psychology, 89*(2), 349-364.

Liu, C. Y., Tan, T., Sun, Y., Zhu, Y., & Zhang, H. (2024). Neuromodulatory co-expression in cardiac vagal motor neurons of the brainstem. *iScience, 27*(4), 107774. https://doi.org/10.1016/j.isci.2024.107774

Mendelowitz, D. (1999). Advances in parasympathetic control of heart rate and cardiac function. *News in Physiological Sciences, 14*, 155–161. https://doi.org/10.1152/physiologyonline.1999.14.4.155

Moore, K. L., Persaud, T. V. N., & Torchia, M. G. (2018). *The developing human: Clinically oriented embryology* (11th ed.). Elsevier.

Neff, R. A., Wang, J., Baxi, S., Evans, C., & Mendelowitz, D. (2003). Respiratory sinus arrhythmia: Endogenous activation of cardiac vagal efferents by a discrete population of brainstem neurons. *Journal of Neuroscience, 23*(13), 4331–4340. https://doi.org/10.1523/JNEUROSCI.23-13-04331.2003

Porges, S. W. (1976). Peripheral and neurochemical parallels of psychopathology: A psychophysiological model relating autonomic imbalance to hyperactivity, psychopathy, and autism. *Advances in child development and behavior*, *11*, 35-65.

Porges, S. W. (1986). Respiratory sinus arrhythmia: Physiological basis, quantitative methods, and clinical implications. In *Cardiorespiratory and cardiosomatic psychophysiology* (pp. 101–115). Springer, Boston, MA.

Porges, S. W. (2001). The polyvagal theory: Phylogenetic substrates of a social nervous system. *International Journal of Psychophysiology, 42*(2), 123–146. https://doi.org/10.1016/S0167-8760(01)00162-3

Porges, S. W. (2003). The polyvagal theory: Phylogenetic contributions to social behavior. *Physiology & Behavior, 79*(3), 503–513. https://doi.org/10.1016/S0031-9384(03)00156-2

Porges, S. W. (2007). The polyvagal perspective. *Biological Psychology, 74*(2), 116–143. https://doi.org/10.1016/j.biopsycho.2006.06.009

Porges, S. W. (2021). Polyvagal Theory: A biobehavioral journey to sociality. *Comprehensive Psychoneuroendocrinology, 7*, 100069.

Porges, S. W. (2022). Polyvagal Theory: A Science of Safety. *Frontiers in Integrative Neuroscience.* https://doi.org/10.3389/fnint.2022.871227

Porges, S. W. (2023). The vagal paradox: A polyvagal solution. *Comprehensive Psychoneuroendocrinology, 15*, 100134. https://doi.org/10.1016/j.cpnec.2023.100134

Porges, S. W. (2024). Disorders of gut–brain interaction through the lens of polyvagal theory. *Neurogastroenterology and Motility*, *e14926*. Advance online publication. https://doi.org/10.1111/nmo.14926

Porges, S. W., & Coles, M. G. H. (1982). Individual differences in respiratory-heart period coupling and heart period responses during two attention-demanding tasks. *Physiological Psychology, 10*(2), 215-220.

Porges, S. W., & Furman, S. A. (2011). The early development of the autonomic nervous system provides a neural platform for social behaviour: A polyvagal perspective. *Infant and child development, 20*(1), 106-118.

Porges, S. W., Bohrer, R. E., Cheung, M. N., Drasgow, F., McCabe, P. M., & Keren, G. (1980). New time-series statistic for detecting rhythmic co-occurrence in the frequency domain: The weighted coherence and its application to psychophysiological research. *Psychological Bulletin, 88*(3), 580–587.

Porges, S. W., Bohrer, R. E., Keren, G., Cheung, M. N., Franks, G. J., & Drasgow, F. (1981). The influence of methylphenidate on spontaneous autonomic activity and behavior in children diagnosed as hyperactive. *Psychophysiology, 18*(1), 42-48.

Porges, S. W., Doussard-Roosevelt, J. A., Portales, A. L., & Greenspan, S. I. (1996). Infant regulation of the vagal "brake" predicts child behavior problems: A psychobiological model of social behavior. *Developmental Psychobiology, 29*(8), 697–712.

Porges, S. W., Macellaio, M., Stanfill, S. D., McCue, K., Lewis, G. F., Harden, E. R., ... & Heilman, K. J. (2013). Respiratory sinus arrhythmia and auditory processing in autism: modifiable deficits of an integrated social engagement system?. *International Journal of Psychophysiology, 88*(3), 261-270.

Porges, S. W., Bazhenova, O. V., Bal, E., Carlson, N., Sorokin, Y., Heilman, K. J., ... & Lewis, G. F. (2014). Reducing auditory hypersensitivities in autistic spectrum disorder: preliminary findings evaluating the listening project protocol. *Frontiers in Pediatrics, 2*, 80.

Porges, S. W., Davila, M. I., Lewis, G. F., Kolacz, J., Okonmah-Obazee, S., Hane, A. A., ... & Welch, M. G. (2019). Autonomic regulation of preterm infants is enhanced by Family Nurture Intervention. *Developmental psychobiology, 61*(6), 942-952.

Pough, F. H., Bemis, W., McGuire, B., & Janis, C. (2023, August 31). *Synapsids and Sauropsids: Two ways of living on land.* Science Trove. https://www.oxfordsciencetrove.com/view/10.1093/hesc/9780197558621.001.0001/isbn-9780197558621-book-part-13

Rajabalee, N., Kozlowska, K., Lee, S. Y., Savage, B., Hawkes, C., Siciliano, D., Porges, S. W., Pick, S., & Torbey, S. (2022). Neuromodulation using computer-altered music to treat a ten-year-old child unresponsive to standard interventions for functional neurological disorder. *Harvard Review of Psychiatry*, Advance online publication. https://doi.org/10.1097/HRP.0000000000000365

Reed, S. F., Ohel, G., David, R., & Porges, S. W. (1999). A neural explanation of fetal heart rate patterns: a test of the polyvagal theory. Developmental Psychobiology: *The Journal of the International Society for Developmental Psychobiology, 35*(2), 108-118.

Richter, D. W., & Spyer, K. M. (1990). Studying rhythmogenesis of breathing: Comparison of in vivo and in vitro models. *Trends in Neurosciences, 13*(8), 282–287. https://doi.org/10.1016/0166-2236(90)90102-K

Richter, D. W., & Spyer, K. M. (2001). Studying rhythmogenesis of breathing: Comparison of in vivo and in vitro models. *Trends in Neurosciences, 24*(8), 464–472. https://doi.org/10.1016/S0166-2236(00)01891-3

Smith, J. C., Ellenberger, H. H., Ballanyi, K., Richter, D. W., & Feldman, J. L. (1991). Pre-Bötzinger complex: A brainstem region that may generate respiratory rhythm in mammals. *Science, 254*(5032), 726–729. https://doi.org/10.1126/science.1683005

Taylor, E. W., Wang, T., & Leite, C. A. C. (2022). An overview of the phylogeny of cardiorespiratory control in vertebrates with some reflections on the 'Polyvagal Theory'. *Biological Psychology, 172*, 108382. https://doi.org/10.1016/j.biopsycho.2022.108382