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Respiratory Sinus Arrhythmia: A literature review

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Abstract

Respiratory sinus arrhythmia (RSA) is a natural variation in heart rate that occurs in synchrony with breathing and serves as a noninvasive indicator of vagal tone. This literature review summarizes current knowledge of RSA and its relevance in physiological and psychological contexts. We review the physiology of RSA, describing how the vagus nerve modulates heart rate variability and how RSA is measured. RSA increases during inhalation and decreases during exhalation, reflecting complex interactions between cardiac and respiratory processes. An evolutionary benefit of RSA has been proposed, as RSA may optimize cardiac efficiency by minimizing cardiac work for a given respiratory demand. We will also examine RSA in emotion regulation. High RSA (greater heart rate variability) has been associated with better emotional regulation and stress resilience, whereas low RSA is often observed in stress and anxiety. Studies are highlighted linking maternal stress and infants' RSA, suggesting early-life stress can dampen an infant's RSA and emotion-regulation capacity. Finally, we explore RSA in dyadic interactions. Research in parent–child and romantic pairs shows that synchronized RSA (physiological synchrony) relates to better social engagement and emotional connection. In therapeutic settings, a client's RSA may indicate openness and a strong therapeutic alliance. Understanding RSA in these domains underscores its potential as a biomarker for emotional and relational health.

Keywords: Respiratory Sinus Arrhythmia; Heart Rate Variability; Vagal Tone; Emotion Regulation; Physiological Synchrony; Therapeutic Alliance

1. Introduction

Respiratory sinus arrhythmia (RSA) is the variation in heart rate that occurs in phase with respiration and is an index of vagal tone (parasympathetic activity of the vagus nerve). What makes RSA particularly valuable is that it can be measured noninvasively. The vagus nerve has widespread effects on the body and brain, including regulating heart rate and social engagement. Monitoring when the vagus is active, and the degree of vagal input, provides useful information to physiologists and psychologists alike. The purpose of this review is to describe RSA and examine how and why it is used in studies of dyadic (two-person) behavior. We first review the physiology of RSA, including what RSA is, how it operates in the body, how it is measured, and its potential evolutionary benefit. Next, we discuss the role of RSA in emotion regulation, highlighting the costs of poor emotion regulation, how RSA reflects emotional regulation capacity, and recent research linking RSA to stress. Finally, we explore RSA in dyadic interactions, covering how RSA synchrony is measured and understood in studies of couples, parents and children, and therapists and clients, and how synchrony in RSA might improve psychotherapy outcomes.

1.1. The Physiology of RSA

The human nervous system is broadly divided into the central and peripheral nervous systems. Each division has multiple components with specialized functions. Figure 1 illustrates that the peripheral nervous system includes 12 pairs of cranial nerves responsible for a variety of functions. One of these is the tenth cranial nerve, the vagus nerve,

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which regulates heart rate, respiration, digestion, and more. RSA refers to heart rate variability observed as fluctuations in the intervals between heartbeats on an electrocardiogram (ECG) that correlate with breathing. High RSA corresponds to greater heart rate variability (and typically lower average heart rate), whereas low RSA indicates reduced variability and higher heart rate.

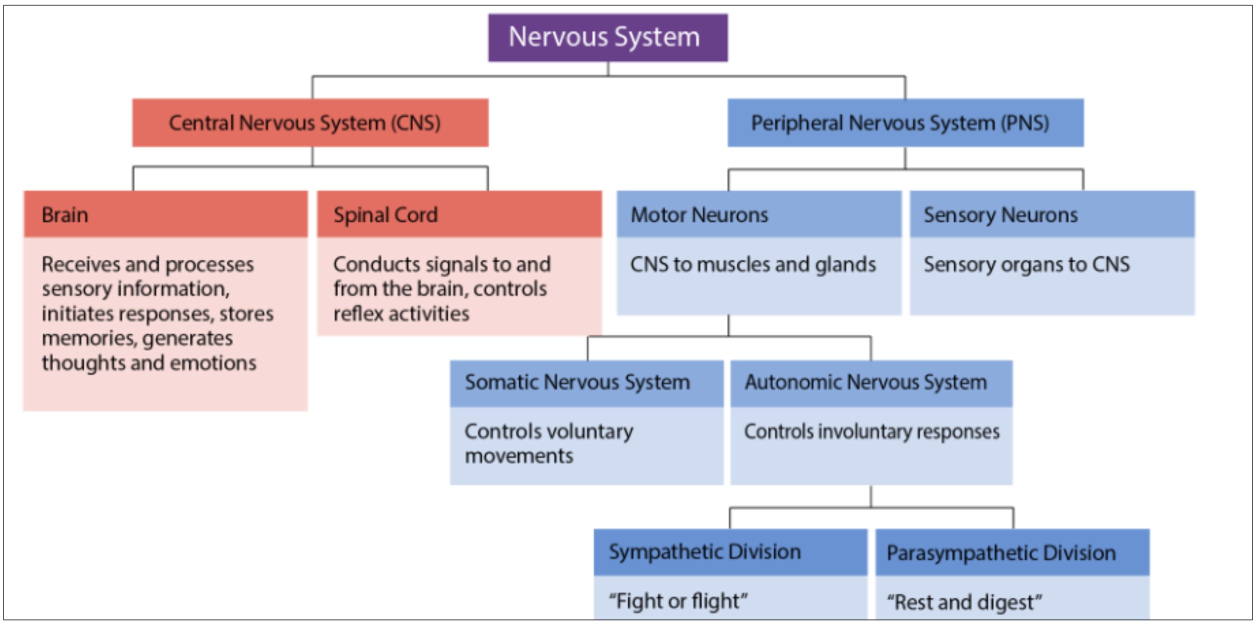

Figure 1 Organization of the human nervous system. Adapted from TopHat Human Anatomy textbook, by L. Jenny et al., 2020, TopHat Online Bookshelf, Human Anatomy, Module 17: Autonomic Nervous System

In terms of direct physiological effect, RSA increases during inspiration and decreases during expiration.[1] Berntson et al. explained that when intrathoracic pressure rises during expiration, venous return to the heart is inhibited, leading to less stretch receptor activation in the blood vessels and a reflexive decrease in heart rate.[1] RSA has been argued to be an optimal indicator of vagal tone. Berntson and colleagues posited that RSA is the most selective measure of vagal activity because it produces the most accurate frequency-transfer function.[1] A frequency-transfer function relates a system's output to a sinusoidal input stimulus.[2] In their formulation, RSA can be modeled as a function of multiple vagal and respiratory factors plus an error term, $RSA = f(Vt, Vp) + \in = f(Vtc, Vta, Vpr, Vpg) + \in$. Here Vt and Vp relate to the resultant function of the tonic and phasic components of vagal cardiac control. Vtc was defined as central vagal drive, Vta was defined as afferent vagal drive, Vpr was defined as respiratory generator, and finally, Vpg was defined as pulmonary gate.[1] This quantitative model underscores that RSA emerges from the dynamic interplay of central vagal drive, afferent vagal feedback, respiratory rhythms, and pulmonary reflexes.

Further research has examined RSA as a model of respiratory–circulatory interaction. Yasuma and Hayano studied the relationship between RSA and cardiovascular function in animal models.[3] The sinoatrial (SA) node—heart's natural pacemaker—receives vagal input, and RSA can be observed by measuring changes in the R-R interval (the time between successive ventricular depolarizations) on the ECG. Yasuma and Hayano[3] used the distances between R-waves (R-R intervals) to assess RSA in anesthetized dogs (see Figure 2).

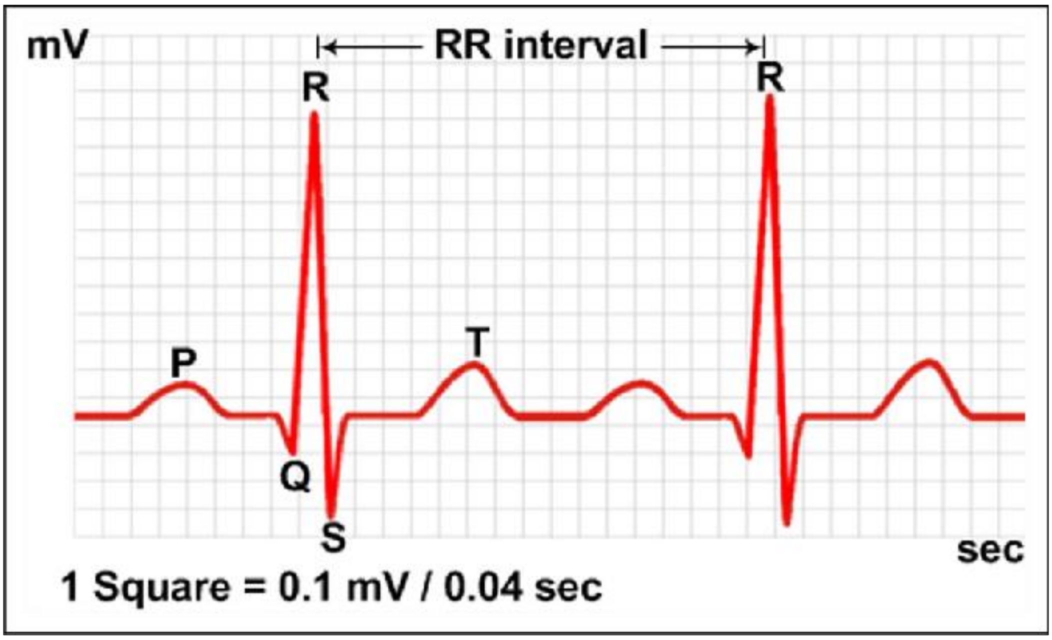

Figure 2 The "R-R" interval on an ECG. Adapted from 'Intelligent health monitoring systems based on smart clothing', by C. Lin, C. Yang, Z. Zhou, and S. Wu., 2018, International Journal of Distributed Sensor Networks, Volume 14, Issue 8, pg. 5

To isolate the contribution of respiration to RSA, Yasuma and Hayano performed bilateral cervical vagotomy (surgical removal of vagus nerve input) in dogs and pharmacologically blocked autonomic activity.[3] Under those conditions, any remaining RSA had to be generated by pulmonary mechanisms. Using artificial pacing of respiration, they demonstrated that heartbeat and breathing can become synchronized and optimized even without vagal feedback. In a follow-up study, Ben-Tal et al. (2012) expanded on the work of Yasuma and Hayano.[3, 4] In that study, the researchers examined RSA as an index of vagal control of the lungs. They found that improved pulmonary gas exchange did not depend on RSA, but they concluded that "RSA minimizes the work done by the heart while maintaining a desired average partial pressure of CO_2".[4] In other words, RSA may have an evolutionary benefit by reducing cardiac effort for a given level of respiratory function. This finding suggests RSA improves perfusion efficiency (blood flow through the lungs and body) by timing heartbeats advantageously within the respiratory cycle.

1.2. RSA in Emotion Regulation

RSA plays an important role not only in cardiorespiratory physiology but also in the regulation of emotions. A large body of research indicates that poor emotion regulation can harm an individual's physical and mental health. As one psychotherapist observed:

"Studies have systematically documented that patients who habitually repress their emotions simultaneously suppress their immune response, rendering them vulnerable… Those who are encouraged to experience and express their feelings demonstrate improvement in immune function, physical condition, and psychological well-being."[5]

This phenomenon is illustrated in Figure 3. Given the high cost of poor emotional regulation, RSA has attracted interest as an objective measure of emotion regulation capacity.[6] Appelhans and Luecken argue that the autonomic nervous system drives the physiological arousal accompanying emotional experiences. When the sympathetic nervous system is activated ("fight or flight"), heart rate increases – sympathetic fibers stimulate the heart's pacemaker to fire more rapidly.[6] Conversely, when the parasympathetic nervous system ("rest and digest") is active, heart rate decreases. Appelhans and Luecken describe heart rate variability as the interplay between these opposing autonomic influences and note that RSA is a convenient index of that interplay.[1, 6]

To quantify heart rate variability, Appelhans and Luecken collected a series of inter-beat intervals via ECG and analyzed the data in the frequency domain.[6] They focused on the R-R intervals (the same measure shown in Figure 2) as the input for a power spectral analysis. This analysis produces a power spectrum: a distribution of the variance in heart rate across different frequency bands. Figure 4 shows an example of a heart rate power spectrum. The magnitude of power in the respiratory frequency range reflects RSA. In their framework, greater power in the high-frequency (respiratory) band corresponds to higher RSA, indicating more robust vagal modulation of the heart.

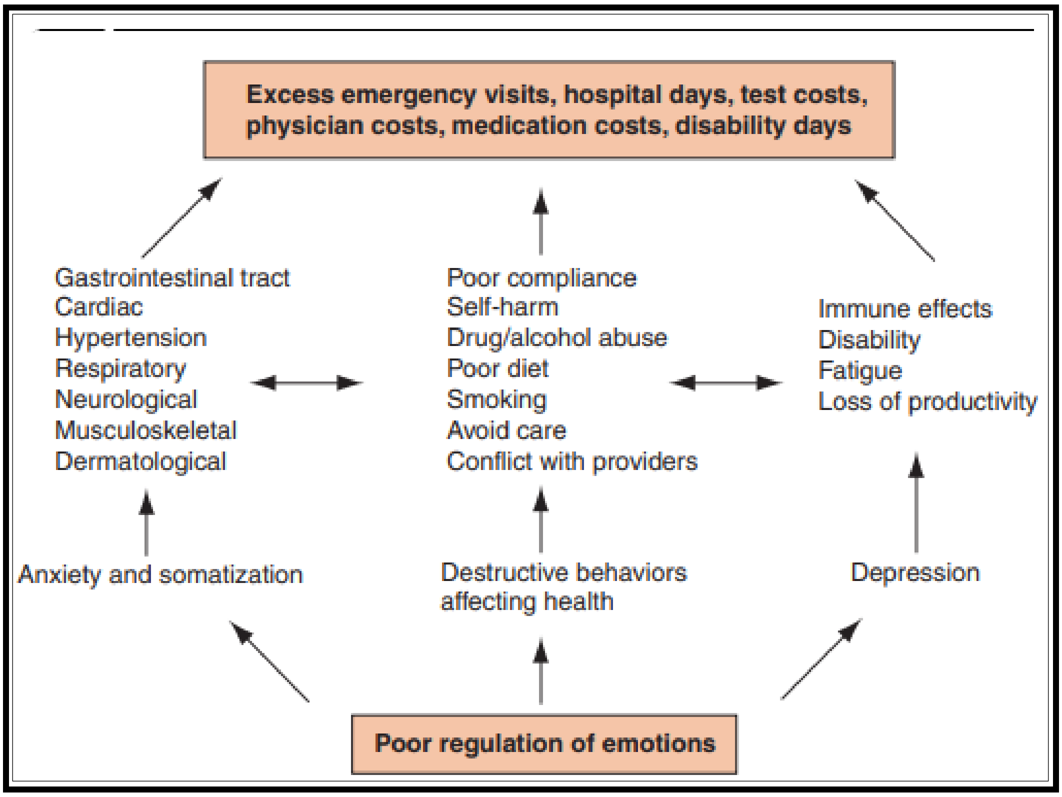

Figure 3 A flow chart depicting the cost of poor emotional regulation. Adapted from 'The cost-effectiveness of short-term dynamic psychotherapy', by Allan A. Abbass, 2003, Expert Review of Pharmacoeconomics & Outcomes Research, Volume 3, Issue 5, pg. 536

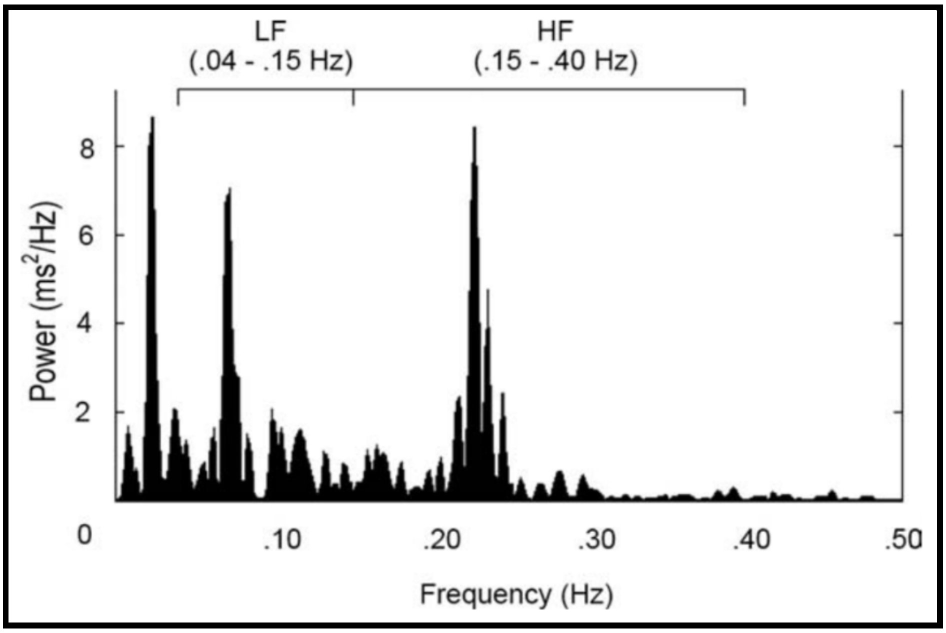

Figure 4 A power spectrum. Adapted from 'Heart Rate Variability as an index of Regulated Emotional Responding' by B. Appelhans and L. Luecken, 2006, Review of General Psychology, Volume 10, Issue 3, pg. 233

With RSA becoming widely accepted as an index of vagal tone and emotional regulation, researchers have begun examining how individual differences in RSA relate to stress responses. Cribbet *et al.*[7] studied the effects of tonic and phasic RSA on the emotional stress response in humans. They measured baseline ("tonic") RSA in 98 participants during a low-stress condition and then recorded RSA changes ("phasic" RSA) while participants discussed a stressful personal experience. Using spectral analysis of the heartbeat data (as described by Appelhans & Luecken), the researchers found that individuals with higher baseline RSA showed a positive association between RSA change and positive affect during stress, whereas those with lower baseline RSA showed a negative association between RSA change and positive affect.[7] In other words, participants who started with higher vagal tone tended to experience an *increase* in positive emotions when their RSA rose under stress, while participants with low vagal tone tended to feel *less* positive emotion with RSA increases. Cribbet *et al.* also concluded that "flexible parasympathetic nervous system functioning is an important component of adaptive stress regulation".[7] This suggests that the capacity to dynamically adjust RSA (and thus vagal output) in response to stress is linked to better emotional outcomes.

Beauchaine[8] extended this line of inquiry by reviewing RSA as a transdiagnostic biomarker of emotion dysregulation. Across many studies, reduced RSA has been consistently observed in individuals with poor emotion regulation. For example, people with anxiety, depression, or conduct problems often exhibit lower resting RSA.[8] This pattern makes an intuitive sense: low RSA reflects low heart rate variability, which occurs when heart rate is elevated or less flexibly controlled, as in states of stress or anxiety. Beauchaine further noted, "Emerging evidence suggests that low RSA and excessive RSA reactivity index poor [emotion regulation] because they are downstream peripheral markers of prefrontal cortex dysfunction."[8] In other words, chronically low RSA or overly reactive RSA responses may indicate an underlying deficit in prefrontal cortex regulation of emotion. Additionally, Beauchaine pointed out that parasympathetic pathways (mediated by the vagus nerve) form a link between prefrontal cortical activity and cardiac function, explaining how RSA can serve as an index of emotion regulatory capacity.[8]

Empirical evidence supporting RSA as an index of emotion regulation continues to grow. One illustrative study examined RSA in the context of prenatal stress. Gray *et al.*[9] assessed RSA in 167 four-month-old infants during the Still-Face Paradigm (a standard social stress test for infants). They found that infants whose mothers had a history of adverse childhood experiences exhibited significantly lower RSA during the stressor (indicating poor emotion regulation), and those infants had weaker recovery (as indicated by return to baseline RSA) after the stressor.[9] Moreover, the study found sex differences in the infants' RSA responses: on average, boys showed higher RSA (greater vagal regulation and stress resilience) during the stressful episode than girls did.[9] The authors speculated that boy's greater RSA under stress might reflect an evolutionary difference in stress reactivity between males and females. Taken together, these findings suggest that maternal stress and trauma can be "transmitted" across generations, affecting an infant's autonomic regulation. Low RSA in infants, in turn, may be a red flag for difficulties in emotional soothing and self-regulation.

1.3. RSA in Dyadic Interactions

RSA takes on special significance in the context of dyadic interactions and interpersonal synchrony. Only a few studies to date have examined RSA dynamics within pairs of individuals. In one such study, Connell et al.[10] investigated RSA in mother–adolescent dyads in the context of maternal depression. They observed 59 mother–child pairs (with adolescents aged 11–17) as they engaged in structured tasks designed to elicit emotional responses and require regulation. During these interactions, both the mothers' and adolescents' RSA were continuously recorded, and trained observers coded the affective dynamics of the dyad in real time. The researchers found that higher maternal RSA was associated with greater flexibility in the dyad's emotional interplay.[10] In fact, maternal RSA emerged as the strongest predictor of dyadic flexibility. Connell et al. noted that "mothers [with higher RSA] exhibit a greater physiological capacity to regulate their emotions despite elevated depression…"[10, p.659] This implies that even in the presence of maternal depressive symptoms, strong vagal regulation (high RSA) in the mother can foster a more adaptable, resilient emotional exchange between mother and child.

Following the topic of maternal depression, Amole et al.[11] studied RSA in mother–daughter dyads. Their sample included 46 mother–daughter pairs, of which 23 mothers had a clinical diagnosis of major depressive disorder. The dyads participated in tasks similar to those in the Connell study (including conversations designed to elicit positive or negative emotions) while their heart rate variability was recorded. The results showed marked differences between clinical and nonclinical dyads. Mother–daughter pairs with a depressed mother exhibited minimal changes in RSA across the tasks and even showed decreases in RSA (negative RSA "slopes") when discussing pleasant topics, indicating blunted or maladaptive physiological responsiveness.[11] In contrast, the control dyads (with no maternal depression) showed positive RSA changes (increases in RSA) during pleasant discussions, reflecting healthy engagement and calming. Amole et al. concluded that the mother's vagal responses play a role in both her own and her daughter's emotion regulation and social engagement.[11] Essentially, if a mother's RSA is inflexible or low (as often seen in depression), her child is likely to exhibit poor emotional regulation and social responsiveness.

Using a related experimental framework, Ferrer and Helm[12] examined physiological co-regulation in romantic couples. They recruited 32 heterosexual couples (ages 18–59) and asked each couple to perform a series of interactive tasks. Some tasks involved imitating each other's behaviors to induce natural synchrony, and in another task partners were explicitly instructed to try to synchronize their physiology (breathing and heart rate) with each other. Throughout these tasks, both respiration and heart rate were measured for each partner. Ferrer and Helm found that the couples were indeed able to achieve physiological synchrony, primarily by aligning their breathing patterns with each other.[12] When one partner adjusted their breathing to match the other's, their heart rate rhythms (and thus RSA patterns) became more synchronized. Further analysis indicated a notable asymmetry: female partners tended to adjust their physiological state to synchronize with their male partners, mirroring the way their day-to-day emotional states were influenced by their partner's emotional states.[12] This suggests that in some heterosexual couples, women might be more physiologically attuned or responsive to their male partner's cues, consistent with broader findings on emotional contagion and empathy in relationships.

Another study leveraged RSA synchrony to distinguish between healthy and dysfunctional dyads. Woltering et al.[13] investigated mother–child dyads where the child had externalizing behavior problems (such as ADHD or conduct problems) versus a control group of mother–child dyads without such issues. A total of 118 children (aged 7–12) and their mothers participated. Each pair engaged in discussions about positive and difficult topics while their heart rates were recorded, and observers rated the level of dyadic attunement (the emotional connection and responsiveness between mother and child). The study found that clinical dyads (those with a child who had behavior problems and often co-occurring maternal stress) showed significantly less physiological attunement. These mother–child pairs had lower RSA synchrony and lower emotional reciprocity across both positive and negative discussions, compared to the control dyads.[13] Even when discussing positive subjects, the clinical dyads did not exhibit the increase in mutual responsiveness that the control dyads did. By contrast, the control mother–child pairs demonstrated higher synchrony and reciprocity, particularly during positive interactions.[13] These findings suggest that disruptions in a child's behavioral or emotional health can manifest in the dyad as reduced physiological and emotional alignment.

As highlighted earlier (see Figure 3), the cost of poor emotion regulation can be severe, which is one reason why effective psychotherapy is important. RSA, as an index of vagal control and a measure frequently used in dyadic interaction studies, may help therapists and researchers understand and facilitate optimal therapeutic outcomes. Geller and Porges[14] have proposed a neurophysiological explanation for the role of RSA in therapy. They emphasize the importance of the therapist's presence: being warm, receptive, and creating a sense of safety for the client. When a therapist behaves in a calming, accepting manner, the client's defensive systems (such as being overly cautious or emotionally closed-off) may deactivate, allowing the client's "social engagement system" to become active.[14] The vagus nerve plays a crucial role in this process, as it provides the parasympathetic control that slows the heart rate during states of safety and relaxation. The same vagal pathways that increase RSA and reduce heart rate are thought to support feelings of safety and trust in social situations.[14] Therefore, in a therapy session, a client's RSA can serve as a real-time indicator of their level of comfort and emotional openness. For example, a higher RSA in the client might signal that they feel safe and engaged, whereas a sudden drop in RSA could indicate stress or withdrawal. The therapist can use such cues (consciously or intuitively) to adjust their approach, helping to "course-correct" the interaction to maintain an optimal therapeutic environment.

To date, there has been only one published study directly examining RSA in a psychotherapy context. Doukas et al.[15] recorded RSA in a sample of 27 women undergoing therapy for complex trauma. In addition to therapy sessions, participants completed an experimental task where they viewed a series of images designed to evoke positive emotion (e.g. pleasant scenes) and negative emotion related to trauma (traumatic imagery). Doukas et al. found that RSA was a significant predictor of the strength of the working alliance between therapist and client.[15] Working alliance refers to the collaborative bond and shared sense of purpose between therapist and client. Clients with higher RSA tended to have stronger working alliances as rated by both clients and therapists. The authors define a strong alliance by mutual trust and agreement on therapy goals and tasks. The study concluded that RSA predicted the strength of the working alliance in therapy.[15] In practical terms, if a client and therapist have established a strong, trusting connection, the client's parasympathetic system is likely more active (leading to higher RSA) during sessions. Conversely, a low RSA or highly erratic RSA in the client might signal tension or a weaker alliance. These findings suggest that RSA is a promising objective tool for gauging a client's engagement and the relational quality of therapy in real time. A therapist attuned to RSA-related cues could potentially tailor their therapeutic presence to foster greater client openness and thus improve therapy outcomes.

2. Conclusion

Research on RSA is flourishing due to its unique status as a noninvasive measure of autonomic activity relevant to both physiology and psychology. This review highlights that RSA serves as a bridge between the body and mind: it reflects the intricate balance of cardiac and respiratory function, and it also indexes a person's capacity for emotional regulation and social engagement. The limited studies of RSA in psychotherapy suggest that understanding physiological synchrony (such as RSA alignment) within therapeutic relationships could deepen our insight into the mechanisms of healing. RSA is commonly utilized in studies of synchrony in various dyads, and future research could explore if intentionally increasing RSA synchrony (for instance, through breathing exercises or biofeedback) leads to stronger therapeutic alliances or higher patient satisfaction with treatment. Building on the work of Doukas et al.[15], clinicians might one day use RSA as a real-time gauge of when a client is most receptive or when the interpersonal connection is strongest, thereby timing interventions for maximum effectiveness. In summary, RSA is a fascinating and valuable phenomenon that exemplifies the interplay of physiological regulation and interpersonal connection, and it holds promise for advancing both scientific understanding and clinical practice.

Compliance with ethical standards

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Disclaimer:

This project was first drafted shortly before the COVID-19 global pandemic. It has been revised recently in 2025 with the goal of publication to the WJBPHS.

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