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How heart rate variability affects emotion regulation brain networks

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Individuals with high heart rate variability tend to have better emotional well-being than those with low heart rate variability, but the mechanisms of this association are not yet clear. In this paper, we propose the novel hypothesis that by inducing oscillatory activity in the brain, high amplitude oscillations in heart rate enhance functional connectivity in brain networks associated with emotion regulation. Recent studies using daily biofeedback sessions to increase the amplitude of heart rate oscillations suggest that high amplitude physiological oscillations have a causal impact on emotional well-being. Because blood flow timing helps determine brain network structure and function, slow oscillations in heart rate have the potential to strengthen brain network dynamics, especially in medial prefrontal regulatory regions that are particularly sensitive to physiological oscillations.

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Introduction

Having high heart rate variability (HRV) is associated with higher emotional well-being [1–3], including being correlated with lower levels of worry and rumination [4], lower anxiety [5], and better regulated emotional responding [6]. Thus, individuals with higher HRV appear to be better at regulating their emotions. However, it is not clear from these correlational studies if HRV is simply an output measure of regulatory brain health, or whether it somehow increases prefrontal regulation effectiveness. In healthy individuals, high HRV is not simply the result of random variability. Instead, much of the variability is due to the heart responding to physiological oscillatory signals such as breathing and blood pressure feedback, such that heart rate slows down and speeds up in a rhythmic fashion at certain frequencies. In this paper, we review findings that suggest that such oscillations in heart rate play a causal role in improving emotion regulation processes. Furthermore, we propose that high amplitude oscillations in heart rate modulate brain oscillatory activity, especially in brain regions associated with emotion regulation, and that daily episodes of synchronized activity within these networks can lead to enhanced functional connectivity strength in these emotion regulation networks even when HRV is not high.

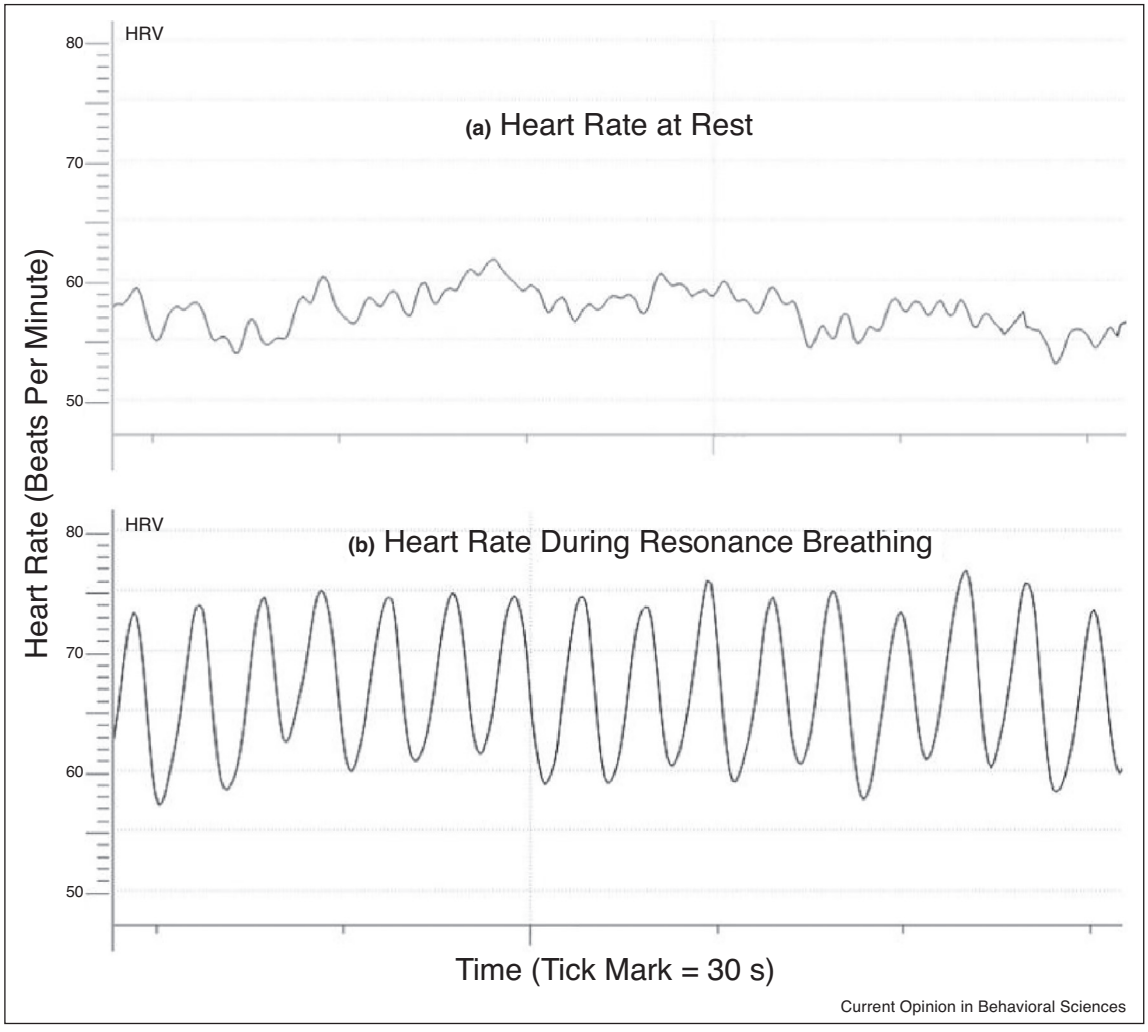
Links between HRV and brain regions involved in emotion regulation

Emerging research indicates that emotion regulation and HRV are associated via the brain regions shared by both systems [7]. For instance, in a meta analysis, HRV was significantly associated with regional cerebral blood flow in ventromedial prefrontal cortex (including anterior cingulate regions) and the amygdala [7]. In both younger and older adults scanned while at rest, higher HRV (measured using the root mean square successive differences; RMSSD) was associated with higher medial prefrontal cortex and amygdala functional connectivity ([8]; see also [9]), a pattern associated with emotion regulation [10]. In addition, among younger and older adults, greater structural thickness in prefrontal regions was associated with greater HRV ([11]; see also [12,13]).

Inducing high amplitude oscillations in heart rate improves emotional well-being

High HRV could be associated with better emotion regulation simply because the same brain regions are involved in regulation of both systems, allowing HRV to serve as an indicator of the functioning of brain regulatory systems. However, recent findings (for review see [14]) suggest that HRV itself influences brain and emotional function. In these studies, participants are taught to increase their HRV by breathing at around 10 s per breath. This .1 Hz frequency is a 'resonance' frequency at which paced breathing induces oscillations in heart rate at an especially high amplitude [15]. Figure 1 shows an example of heart rate at rest in a healthy individual (panel A) followed by heart rate during paced breathing at their resonance pace (panel B). In resonance breathing HRV biofeedback studies, participants get feedback on how successfully they are increasing heart rate oscillations [15]. They typically engage in HRV biofeedback for at least 20 min a day for several weeks. A recent meta-analysis of 24 studies revealed that HRV biofeedback reduced self-reported

Figure 1



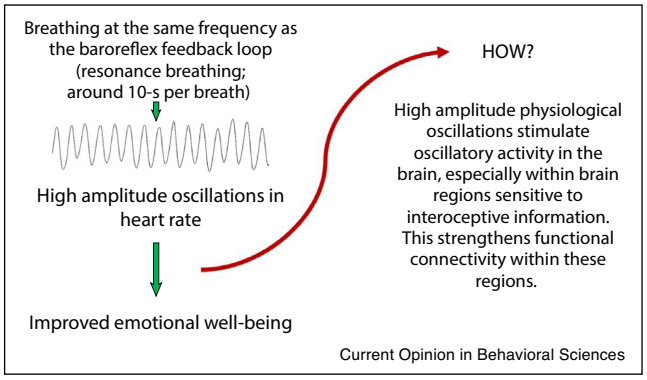
(a) An example of heart rate variability during about a 2.5 min time period during quiet rest. **(b)** The same person's heart rate during resonance breathing during another 2.5 min time period.

stress and anxiety with a large effect size [16]. For instance, in one study, basketball players scoring high on anxiety were randomly assigned to HRV-biofeedback during resonance paced breathing, to an active control, or a no-contact control condition [17]. Participants completed sessions 10 days in a row for 20 min in each session and were tested before and after the 10-day intervention and again a month later. The intervention reduced state anxiety, and increased performance on standardized tests of basketball dribbling, passing and shooting. HRV biofeedback also has other positive effects on emotions. Coronary artery disease patients randomly assigned to HRV biofeedback during resonance breathing instead of a wait-list control showed decreased expressive and suppressive hostility and these effects were maintained a month after the 6-week intervention ended [18]. Likewise, veterans with post-traumatic stress disorder randomly assigned to HRV-biofeedback during resonance breathing showed reduced symptoms after 8 weeks of HRV-biofeedback whereas those assigned to treatment as usual did not show significant reductions in symptoms [19]. In addition, patients with post-stroke depression randomly assigned to treatment-as-usual in addition to HRV biofeedback during resonance breathing showed greater reductions in some indices associated with depression than those not assigned to HRV biofeedback [20]. Thus, in these studies, a series of HRV-biofeedback sessions using resonance paced breathing enhanced emotional outcomes (Figure 2).

Why resonance breathing increases the amplitude of heart rate oscillations

The studies reviewed above using HRV biofeedback during paced breathing take advantage of the fact that

Figure 2



(Article summary figure). How resonance breathing could lead to improved emotional well-being by stimulating functional connectivity of emotion regulation networks within the brain.

two physiological rhythms that have a strong influence over the heart rate can be coordinated to induce high amplitude heart rate oscillations. The first of these physiological rhythms is the baroreflex. The vascular branch of the baroreflex has a lag time of approximately 10 s [21]. When vessels are stretching, baroreceptors signal via the brainstem to the heart to slow down the pace of heartbeats. There is a few-second delay in this feedback loop (between 4 and 6.5 s [22]) that creates oscillations in heart rate that take twice as long as the delay (from 0.075 to 0.12 Hz, depending on the individual) to complete a full oscillatory cycle [14,22]. The second major influence over HRV is breathing. As we breathe in, heart rate tends to increase and as we breathe out, heart rate tends to decrease [23], although with a phase delay [24]. We usually breathe at a faster frequency (between .15 and .4 Hz) than the baroreflex. However, unlike the baroreflex, which has a fixed frequency, we can alter the pace of our own breathing. When breathing is slowed down to the same frequency as the baroreflex feedback loop, this creates resonance, a non-linear effect that is greater than an additive effect of the two influences. Thus, at an individual's resonance frequency, there is the potential for high amplitude oscillations in heart rate.

A fascinating relevant phenomenon is that, in many meditative and religious chanting practices, breathing slows to around a 10-s (.1 Hz) rate and heart rate oscillates at this frequency [25–29]. For instance, reciting either the rosary Ave Maria prayer or a yoga mantra leads to breathing at a 10-s/breath rate and increased blood pressure and heart rate oscillations at that .1 Hz resonance frequency [25]. Hypotheses about the mechanisms of the positive effects of meditative practices typically focus on the role of attentional training and body awareness [30]. In contrast, there has been little focus on the role of physiological rhythms induced by the meditative practice.

High amplitude heart rate oscillations should promote functional connectivity, especially in brain regions involved in emotion regulation

We propose that episodes of high amplitude oscillations in heart rate (like those observed during meditative practice or HRV biofeedback) promote functional connectivity between certain brain regions, in particular among brain regions involved in emotion regulation. Why might this be the case?

First of all, brain activity is fueled by oxygen transported by blood, and so should be affected by oscillations in blood flow. Indeed, heart rate contributes to blood-oxygen level dependent (BOLD) fluctuations during functional magnetic resonance imaging (fMRI) [31–33]. Strong phase coupling of heart rate interval and BOLD oscillations have been observed in the mid cingulate and posterior cingulate regions at around the .1 Hz frequency [34]. These hemodynamics are likely to impact neural activity. In particular, oscillations in blood flow may lead to oscillations in the sensitivity of local cortical circuits to sensory stimuli [35].

Different brain regions vary in how long it takes for blood to reach them, with distant brain regions sometimes having similar vascular delays. Estimating vascular delay times for each voxel in an fMRI image and then running independent component analyses reveals components that resemble commonly identified resting state networks [36]. Resting state networks reflect brain regions that activate in correlated fashion at slow frequencies (<.1 Hz; [37]). It is intriguing that just knowing the vascular delays of different brain regions provides enough information to partially reconstruct resting state networks [36]. Indeed, part of what may lead some brain regions to develop coordinated network activity with each other may be their similar timing of blood delivery. Increasing the amplitude of blood flow oscillations via resonance breathing increases the impact of these coordinated vascular activities and thereby further stimulates networks that were shaped in part by blood flow patterns. Repeated brief episodes of coordinated activity within a network can strengthen its internal pathways, promoting greater functional connectivity during rest (e.g. [38,39]).

In addition to timing, regional differences in blood flow volume are also associated with functional connectivity [40]. Brain regions with high resting cerebral blood flow also show high functional connectivity with other brain regions, and the correlation between functional connectivity strength and blood flow is higher for measures of long-range than for short-range functional connectivity [40]. Brain regions showing strong cross-subject correlations between functional connectivity strength and blood flow include medial prefrontal cortex, anterior and posterior cingulate, and insula [40]. Thus, these brain regions associated with emotion regulation are among those that

experience high regional blood flow and serve as hub regions for brain functional connectivity. These characteristics make oscillations in blood flow especially likely to impact these brain regions.

Breathing also influences brain rhythms. Breathing volume and pace help determine arterial CO_2, which is a cerebral vasodilator and is expelled during breath exhalation. Brain regions differ in the timing and strength of their responses to these CO_2 fluctuations, likely related to their proximity to large vessels, with strong correlations seen in insula and midline cingulate regions [41,42]. Breathing causes respiration-synched oscillations across much of the neocortex and gamma power waxes and wans depending on the respiratory oscillation phase [43]. Breathing through one's nose synchronizes oscillations in olfactory cortex as well as the amygdala and hippocampus [44]. In these limbic regions, nostril breathing entrains higher frequency oscillations in the delta, theta and beta ranges to the respiratory phase [44]. Thus, the breathing component of resonance breathing biofeedback practice should also contribute to neural oscillatory activity, especially in the limbic regions during nostril breathing.

Heartbeats also cause EEG responses known as heartbeat-evoked potentials that are particularly prominent in brain regions associated with interoceptive sensation and emotion, including medial prefrontal cortex, cingulate cortex, insula, and amygdala [45,46]. Thus, heartbeats should be especially likely to influence brain rhythms in these brain regions. Consistent with this, BOLD activity in the ventromedial prefrontal cortex covaries with heart rate more than does activity other brain regions [47], and as already reviewed, in general, medial prefrontal/anterior cingulate regions show activity associated with HRV [7].

In summary, resonance breathing stimulates high amplitude oscillations that can influence brain rhythms via several channels, including fluctuations in blood flow, CO_2 levels, and sensory input from breathing and from heartbeats. These channels each are especially likely to modulate activity in brain regions associated with emotion regulation networks [48].

Slow oscillations can modulate faster frequencies of neural activity

In the previous section, we laid out the case that resonance breathing is likely to lead to oscillations in brain activity. Here we argue that, in addition to provoking oscillations at the same frequency, resonance breathing should also modulate faster oscillatory activity. The power density of EEG is inversely proportional to frequency, such that more powerful and widespread slow oscillations can modulate weaker but faster local oscillations [49,50]. Slow oscillations are also critical for brain networks, because the limited number and speed of neuronal connections connecting distant regions mean that large-scale brain networks can only oscillate in tandem during slow oscillations [50].

The ability of lower frequency oscillations to modulate the phase of higher frequency oscillations leads to a hierarchical structure for EEG. For instance, in awake macaque monkeys, delta phase (1–4 Hz) modulates theta phase (4–10 Hz) and theta modulates gamma phase (20–50 Hz) amplitude, with these oscillations controlling baseline excitability and leading to phasic oscillations in responsiveness to stimuli [51]. Activity at one frequency is especially likely to modulate activity at other frequencies that are multiples of that frequency, a phenomenon known as harmonic frequency. Indeed, one speculative proposal is that the heart rate is the basic frequency and scaling factor for EEG frequency domains [52]. EEG is categorized into a set of different frequency bands (delta, theta, alpha, beta, gamma). The center frequency of each of these frequency bands (estimated at 2.5, 5, 10, 20 and 40 Hz, respectively) is twice as high than the previous lower frequency [52]. If the harmonic sequence of EEG frequency bands is extended down from delta to slower oscillations, the next lower one is 1.25 Hz, which, at 75 beats per minute, is close to the average resting heart rate (e.g. [53]), suggesting that heart rate may be a basic frequency that serves as a scaling factor (depending on individual differences in average heart rate) for the EEG frequency domains [52]. Furthermore, if one continues going down to the subharmonic frequencies, one of the frequencies overlaps with high frequency HRV range influenced by breathing and another overlaps with the low frequency HRV range influenced by baroreflex feedback [52]. Consistent with these harmonic relationships, during sleep high frequency HRV shows synchronization with each of the different EEG frequency bands [54]. Furthermore, during wakefulness, the EEG spectral peak frequency (i.e., the alpha band peak frequency) is correlated with heart rate and this correlation decreases as sleep depth increases [55].

Thus, low frequency oscillations induced by resonance breathing should be able to promote functional connectivity between non-adjacent brain regions while also modulating oscillations at higher EEG frequency bands. Studies examining the oscillatory properties of brain activity are consistent with this notion that oscillations in the resonance frequency range help organize and modulate activity at higher frequencies. For instance, oscillations in prefrontal oxyhemoglobin in the frequency band between .07 and .13 Hz were coupled with EEG alpha and/or beta power oscillations [56]. Intracranial recordings from human posteromedial cortex revealed that the magnitude of cross frequency theta-to-gamma modulation fluctuated at around a 0.1 Hz frequency [57]. Thus, oscillations in brain activity at around the resonance frequency can modulate interactions among faster frequency signals (see also [58]).

Another potential pathway of action of resonance frequency heart rate oscillations on the brain

Stimulation of the baroreflex with resonance paced breathing is also likely to modulate brainstem arousal pathways. As already touched upon, as part of their feedback loop, baroreceptors project to the nucleus of the solitary tract and stimulate both sympathoinhibitory and vagal cardioinhibitory pathways that decrease heart rate [59]. In addition to its effects on the heart, the baroreflex pathway also interacts bidirectionally with brainstem and forebrain regions that regulate arousal [59]. Breathing also stimulates brainstem arousal centers and breathing and blood pressure signals interact in affecting sympathetic activity (e.g. [60]). Thus, resonance breathing should modulate arousal. Most likely, these effects will involve oscillatory influences. Consistent with this possibility, during slow breathing, muscle sympathetic nerve activity decreases in a phasic fashion, reaching the same peak level as in control conditions but showing phasic segments of suppression [61–63]. If inducing high amplitude oscillations in heart rate phasically suppresses sympathetic action while stimulating parasympathetic action, this could help explain the stress-reducing and anxiety-reducing effects of resonance breathing [16].

Conclusions

Past research has focused on heart rate variability as a downstream measure, rather than something that itself affects emotion regulation. For instance, the Neurovisceral Integration Model proposed that the medial PFC along with a core set of neural structures integrates information from different system to regulate the heart, and that HRV provides an index of the effectiveness of this 'core integration' system [7]. Furthermore, previous research has not distinguished whether it is random noise or increases in the amplitude of oscillatory activity that is the key component of HRV that is associated with better emotional outcomes. The findings we outlined in this paper suggest that heart rate oscillations can enhance emotion by entraining brain rhythms in ways that enhance regulatory brain networks.

Conflict of interest statement

Nothing declared.

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