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Following the Rhythm of the Heart: HeartMath Institute's Path to HRV Biofeedback

Rollin McCraty[1]

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Abstract

This paper outlines the early history and contributions our laboratory, along with our close advisors and collaborators, has made to the field of heart rate variability and heart rate variability coherence biofeedback. In addition to the many health and wellness benefits of HRV feedback for facilitating skill acquisition of self-regulation techniques for stress reduction and performance enhancement, its applications for increasing social coherence and physiological synchronization among groups is also discussed. Future research directions and applications are also suggested.

Keywords Heart rate variability · HRV · Biofeedback · Coherence · Entrainment · Resonance · Heart-brain · Physiological synchronization

Introduction

The path that led my colleagues and me to heart rate variability (HRV) research and the subsequent development of HRV biofeedback technologies started in 1987 when I first met Doc Childre, who a little later, founded the HeartMath Institute. Prior to this, I was a communication systems engineer at Motorola and found that I was never satisfied with the explanations I had been taught about the deeper nature of electromagnetism, even though much was understood in terms of how to use these seemingly mysterious electromagnetic "fields" to carry information over great distances. This curiosity led me to start exploring other perspectives, which eventually led me to leave Motorola and move to California where I ended up getting a master's degree in consciousness studies. This was my first exposure to biofeedback, various types of mindfulness and meditation practices, and methods of measuring one's autonomic nervous system responses as a feedback signal, etc. I then co-founded a highly successful company in the field of electrostatics and although I continued to meditate and could achieve some quite expanded inner states, I would often find myself stressed and quick to get triggered, feeling frustrated, impatient and judgmental of others in my day-to-day life. It was during this period that I met Doc Childre, who, through his studies and experiences, came to the conclusion that the energetic heart really is the bridge to one's higher awareness capacities. Although I was aware of the many references to the heart as a source of intuitive inner guidance, wisdom, and unconditional love, I considered them to be metaphors and never really took this seriously. I decided to sincerely try the heart-focused practices to access the heart's intuitive guidance Doc had suggested. Over the next few months I was surprised and delighted with the positive effects it had on my self-awareness, meditations, personal and business decisions and relationships and my ability to regulate my thoughts and emotions. These experiences and intuitive promptings from my heart led me to sell my ownership in the company and accept an invitation to help Doc and others found a new non-profit research and educational organization to explore how the qualities associated with the heart could be related to improved healthy function, social harmony and helping people more effectively navigate an increasingly stressful and polarized world.

The HeartMath Institute received its official IRS non-profit status in 1991 and shortly thereafter, the initial training courses we had been developing were offered publicly and the first books were published (Childre, 1992a, 1992b; Childre, 1992a, 1992b). Mike Atkinson and I started our applied research laboratory where we first established cell culture, electrophysiology and Holter recording and analysis

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✉ Rollin McCraty
rollin@heartmath.org

[1] HeartMath Institute, Boulder Creek, USA, CA

labs. The first intervention-focused study we conducted was with a population of 38 individuals with acquired immune deficiency virus (AIDS) in January of 1993 (Rozman et al., 1996). At that time there were very few published studies on positive emotions. Our first experiments were focused on the physiological correlates of positive emotions such as appreciation and compassion, as well negative emotions such as frustration, or anger. We sought to determine which physiological variables were most sensitive to and correlated with changes in emotional states by analyzing many different physiological measures such as heart rate, electroencephalogram (EEG) and electromyography (EMG) activity, respiration, skin conductance, etc. One of the many things we looked at was the frequency spectrum of the electrocardiogram (ECG) over different time intervals (McCraty et al., 1993). Surprisingly, these spectra appeared to reflect one's emotional state and became our first form of heart-related biofeedback. We set up a process where the ECG spectra could be viewed in real-time. Our participants found it fascinating to see the spectra change as they intentionally changed their emotional states.

We were able to show that the primary underlying factor responsible for the differences in the frequency structures in the ECG spectra were the patterns of the changing time intervals between the R-waves in the ECGs. This observation led us to look at the patterns in the beat-to-beat changes in the time intervals between consecutive pairs of heartbeats, or what is known as heart rate variability (HRV). We explored many things in these early years, such as phase relationships between respiration, beat-to-beat blood pressure (pulse transit time) and heart rhythms, various measures of heart-brain interactions (McCraty, 2002), heart-brain synchronization between pairs of participants (McCraty, 2004) and the effects of emotions on hormonal and immune system variables (McCraty et al., 1998; Rein & McCraty, 1994; Rein et al., 1995). What stood out the most was that the pattern of the HRV rhythm (typically independent of changes in the amount of HRV) was reflecting peoples' emotional states and that positive emotions tended to create a dramatic change in the pattern of the HRV rhythms. In this state, that we first called the "entrainment state" and later changed it to "physiological coherence" (also referred to as cardiac coherence, heart coherence or heart rhythm coherence), we found that the heart rhythms, blood pressure, respiration rhythms and often a very low frequency brain rhythm were frequency entrained. By having participants of differing ages vary the frequency of their breathing rhythms over a wide range (fast to slow), we found a frequency range or band width in which this entrainment could occur, which was centered around 0.1 Hz. When these rhythms entrained, regardless of the frequency, there was a large state-specific increase in the amplitude of the HRV waveform, although there were individual differences in the specific frequency where the maximum amplitude occurs. This "entrainment range" within which frequency pulling and entrainment could occur is not the same as the traditional bands used for HRV (Tiller et al., 1996).

After much discussion with our Scientific Advisor Board members, we changed the terminology to describe this state from the entrainment state to coherence for a few reasons. It was clear that various rhythms were not only frequency entraining, but cardiovascular system resonance, and synchronization of other rhythms such as EEG and craniosacral rhythms (Chikly, 2003) were also occurring in this optimal state. In addition, the coherence state was related to one's emotions and the informational patterns that could be measured in the heart's magnetic field external to the body which had implications for an energetic communication exchange between individuals and in social dynamics. We needed an overarching concept that embraced entrainment, resonance, synchronization, and capacity for self-regulation. We landed on coherence as the ideal overarching concept as it always implies correlations, connectedness, consistency, efficient energy utilization and typically refers to a global order, where the whole is greater than the sum of its individual parts. It also included the mathematical concepts and tools for assessing cross-coherence, entrainment, auto-coherence and synchronization not only within one's physiology but also between individuals (McCraty et al., 2009a, 2009b; McCraty, Childre 2010; Tiller et al., 1996).

It was clear that the physiology was shifting into an optimal state and oscillating at a resonant frequency inherent to the heart, brain, lungs and vascular system as a whole. We also found that although the respiratory, beat-to-beat blood pressure and heart rhythms remained frequency entrained, the phase relationships among them were different when one intentionally changed their breathing rhythm vs normal physiological functioning. We also found that the natural entrainment frequency could and did vary depending on the positive emotion they were experiencing (McCraty et al., 1995a, 1995b). We published a study in the American Journal of Cardiology showing how states of anger and appreciation are reflected in the HRV patterns and power spectra (McCraty et al., 1995b). It is important to note that in this study (and several others), (McCraty et al., 1995a, 1995b; Tiller et al., 1996) participants were not instructed to alter their breathing rhythm, rather, they were instructed to self-induced various emotions. We found that participant's respiration rhythms were changing in response to the emotions they were experiencing rather than consciously altering their breathing. This suggests that higher level brain systems above the cardiorespiratory integration centers in the dorsal vagal complex involved in emotional processing and experience (amygdala, etc.) are unconsciously modifying the breathing rhythm (McCraty et al., 2009b).

In essence, we found that the rhythmic patterns of heart activity were associated with the subjective activation of distinct emotional states, and that the heart rhythm pattern covaried with the emotions people experienced. We found distinct rhythmic HRV patterns that were readily apparent in the heart rhythm that matched the subjective experience of different emotions when repeated at different times and in different populations. It has since been shown that analysis of the HRV pattern alone can be used to detect specific, discrete, emotional states with around 75% accuracy (Leon et al., 2010).

In the early versions of the self-regulation techniques we developed, we did not include any reference to breathing deeper and slower or at a specific rhythm. One of the reasons for this was that we had found that nearly half of the people who were not previously familiar with breathing practices, found paced breathing to be uncomfortable and unpleasant after about 1-min. However, when teaching the self-management techniques, it was clear that in populations who were highly stressed or who had lower emotional self-awareness or health challenges were not able to shift into the coherent rhythm by activating a positive emotional state alone. We found a good balance by modifying the first step that is currently used in most of the HeartMath empowerment techniques, to “Heart-Focused Breathing”. In addition to the heart focus (which we consistently found as an important aspect) in the original versions, we instructed them to “focus your attention in the area of the heart. Imagine your breath is flowing in and out of your heart or chest area, breathing a little slower and deeper than usual. Find an easy rhythm that’s comfortable”. We then have them move to the second step which typically involves breathing or drawing in a feeling of ease or a regenerative emotion or attitude (Childre et al., 2016; McCraty et al., 2016). We consistently found that with this approach and a little practice, most people were able to use the breath to “jump-start” the shift into the coherence rhythm and settle into their natural resonant frequency and sustain the coherent state for much longer periods without experiencing the discomfort associated with only doing paced breathing.

In the lab it was easy to set up real-time HRV feedback so that participants could see the pattern of their HRV change into a sine wave-like pattern as they practiced the mental and emotional self-regulation techniques we had developed. They consistently reported that the visual feedback was motivating and helpful when they could see how their physiology “shifted” and helped them learn to sustain the coherent state for longer periods. In the early to mid-90’s, the trainers who were delivering our stress management and performance enhancements programs to schools, businesses, healthcare providers, etc. requested a way for the participants they were training to be able to see the changes in their heart rhythms during in-person trainings. I visited Biopac® systems shortly after they had released their data acquisition software (AcKnowledge) and the MP series of hardware devices. We decided to use their MP 30, a 4-channel data acquisition system with laptops so the trainers could have a portable HRV biofeedback system. They had to travel with an extra suitcase and place ECG electrodes on one or two of the participants in order for the group to see how the techniques worked with others from their own group. This was a huge “hit” with the audiences and was reported as significantly enhancing their learning and motivation to use the self-regulation techniques in day-to-day life.

Partly based on the feedback we were getting from the training community, we developed a low cost, consumer-friendly HRV coherence biofeedback training system in our laboratory. This took several years and involved a lot of trial and error at the various stages of development. We first needed to develop a scoring algorithm that would assess the level of HRV coherence. This was a bit of a challenge as it needed to work with individuals across the age span and with any frequency in the coherence range which varies between individuals and even within a session. It also needed to track and feedback a real-time coherence score which was independent of heart rate and the amplitude of the HRV rhythm. The coherence scoring algorithm we developed identifies the maximum peak in the 0.04–0.26 Hz range of the HRV power spectrum, calculates the integral in a window 0.030 Hz wide, centered on the highest peak in that region, and then calculates the total power of the entire spectrum over a 64-s window that is updated every 5-s. The Coherence Ratio is formulated as: (Peak Power / (Total Power – Peak Power)) (McCraty et al., 2009b; McCraty & Childre 2010). In order to make the system more engaging to users, we developed several games that were controlled by the user’s level of HRV coherence and included several feedback display options. Having done our own studies confirming the high correlations between pulse photoplethysmogram (PPG) and ECG derived HRV, we developed pulse sensors (for the ear or finger) rather than using the ECG which made it consumer-friendly.

Although neither of us can remember the exact year we first learned of each other’s HRV research, it was in the late 1990s or early 2000s when Paul Lehrer met Deborah Rozman, who is one of my HeartMath colleagues, during a chance meeting. Dr Lehrer visited the Institute a few years later where I first learned of the late Dr Evgeny Vaschillo’s research, to whom this special issue is dedicated. Although I did not have the opportunity to get to know him well, we did have the chance to meet at a biofeedback conference. I appreciated learning of his and Dr. Lehrer’s independent research showing that HRV biofeedback led to lasting increases in baroreflex gain, independent of respiratory and cardiovascular changes, thus demonstrating neuroplasticity of the baroreflex system (Lehrer et al., 2003).

HRV Biofeedback Technologies

To the best of my knowledge, the first device designed specifically for HRV biofeedback to be introduced to the public and healthcare professionals was called the Freeze-Framer™. This system was released in 1999 by HeartMath LLC under a technology transfer agreement. The name Freeze-Framer was a durative of the self-regulation technique called Freeze-Frame® (Childre, 1998). With the success of the Freeze-Framer and many requests for a more portable device that did not require a laptop, a standalone HRV coherence device called the emWave® Personal Stress Reliever was introduced in 2006. The Freeze-Framer was renamed as the ewWave® PC in 2007 and an updated version called the emWave® Pro was released in 2013. An additional capability was added to the emWave Pro in 2015 (emWave Pro-Plus) enabling it to also be used in research and clinics for short-term HRV assessments and analysis. This HRV analysis module has data editing capability and calculates all of the standard time and frequency domain HRV variables as well as HRV coherence. In addition, it has guided instructions for a 1-min paced deep breathing assessment with age-adjusted normative HRV values. We found that this short-term HRV assessment has the highest correlations to 24-h HRV assessments, making it an ideal health risk screening tool and for assessing changes in HRV over time (McCraty et al., 2019; Six Dijkstra et al., 2018). In early 2013, the Inner Balance™ Trainer software and the first sensor for smart phones was introduced, which has greatly expanded the general public's use of HRV biofeedback to facilitate skill-acquisition and on-going use of self-regulation skills in day-to-day life. The HeartCloud was also introduced at the same time as the Inner Balance, which allows HRV data from any of the devices to be uploaded and stored in the cloud servers, and when permission is granted, allows coaches, mentors or researchers to see and track client's session data. Due to the COVID-19 pandemic, there became a need for remote HRV assessments. To meet this need HeartMath LLC added the capability for the Inner Balance app to be used for HRV assessments where the inter-beat-interval (IBI) data that is uploaded to the HeartCloud can be directly downloaded into the emWave Pro-Plus software for editing and analysis.

More recently, our laboratory developed and released an app designed to help support our Global Coherence Initiative community (McCraty & Al Abdulgader, 2021; McCraty & Deyhle, 2015). The Global Coherence™ App is designed to assess and display the average coherence of groups, in addition to personal coherence scores. Users can set up their own groups of any size (family, work or sports team, state or country, etc.) and see the real-time group coherence scores as well as track the number of coherence points the group has accumulated over time. This app also includes a real-time global map showing the relative location of all the participants who are using the app at the same time. It works with the same family of wired or Bluetooth Inner Balance sensors, or the phone's camera can be used as the pulse sensor. An additional feature of this app is that is allows for the collection of time-synchronized HRV data from participants located anywhere in the world in real-time. This enables us to conduct studies on HRV synchronization among group members in both local and non-local contexts (McCraty, 2017).

Health and Wellness Benefits of Self-Regulation and HRV Biofeedback

Most of our clinical, workplace and educational studies using HRV coherence feedback technologies included training in heart-focused self-regulation techniques that are designed to shift one's physiology into a more coherent state when one is currently experiencing stress or wanting to enhance upcoming performance. We find this combination to have a synergistic effect that has helped transport HRV biofeedback from clinics into educational and organizational settings as well as to the general public. A comprehensive review of the clinical and organizational studies is beyond the scope of this paper and has been discussed elsewhere (McCraty, 2016; McCraty et al., 2009b; McCraty & Childre 2010; McCraty & Zayas, 2014). Numerous studies that have used HRV coherence feedback technology to facilitate skill acquisition of self-regulation techniques have found significantly improved key markers of health, wellness and performance in many healthcare, law enforcement, corporate, military and educational settings (Alabdulgader, 2012; Beckham et al., 2013; Bedell, 2010; Berry et al., 2014; Bradley et al., 2010; Burch et al., 2018; Celka et al., 2020; Criswell et al., 2018; de Visser et al., 2016; Devi & Sheehy, 2012; Dziembowska et al., 2015; Edwards, 2017; Edwards, 2014a, 2014b; Field et al., 2021; Field et al., 2022; Ginsberg, 2010; Hurtado et al., 2020; Jasubhai, 2021; Jester et al., 2018; Kim et al., 2019; Laudenslager et al., 2019; Lemaire, 2011; Li et al., 2022; Lloyd, 2010; Lord et al., 2019; Lutz, 2014; May,et al., 2018; McCraty & Atkinson, 2012; McCraty et al., 2000; McCraty et al., 2009a, 2009b; McCraty et al., 2003; McCraty et al., 1999; McCraty et al., 1998; McCraty & Nila, 2017; McLeod & Boyes, 2021; Pyne et al., 2018; Rijken et al., 2016; Saito et al., 2021; Sarabia-Cobo, 2015; Sutarto et al., 2020; Thurber, 2010; Trousselard et al., 2015; Wang et al., 2016; Weltman et al., 2014).

Scientific Mentors

I would be remiss if I did not acknowledge our Scientific Advisory Board members and the mentoring I benefited from in the early years of our research. Our interests in conducting research on love, compassion, the energetic field of the heart, and intuition were what seemed to attract most of our scientific advisors. I cannot mention them all, however, it's relevant to mention those who were more involved in our early HRV research and HRV biofeedback journey. The cardiologists were Dr Paul Rosch, founder and president of the American Institute of Stress, Dr Donald H Singer, who was the first to correlate low HRV with increased risk of sudden cardiac death (Singer et al., 1988) and show that high levels of HRV are a marker of healthy aging (Singer, 2010). Dr Stewart Wolf Jr who conducted the Roseto community studies and was the first to show that poor HRV recovery after a heart attack was the strongest predictor of future mortality (Wolf, 1992). Dr John Andrew (Drew) Armour, who is a leading figure in the Neurocardiology research community, coined the term "heart brain" (Armour & Ardell, 1994; Armour, 1991, 2003b). The neuroscience members were Dr Karl Pribram, who conducted pioneering research into the functions of the brain's limbic system, frontal lobes, temporal lobes, and their roles in decision making and emotion, and developed the holonomic theory of memory and perception (Pribram, 1967, 1991, 2013). Dr Joe Kamia, who is generally credited as the first to use EEG biofeedback (Kamiya, 1977), and David Joffe who founded Lexicor Medical Technology and developed one of the first professional EEG biofeedback systems. There were also several physicists on our board, but it was Dr William (Bill) Tiller, who at that time, was department chair of the material science and engineering at Stanford University and was an expert in the field of crystallization, and also was interested in the study of subtle energy and intentionality. He was the physicist most directly involved in the HRV related studies as well as the early energetics related studies (Tiller, 1997; Tiller et al., 1996; Tiller,et al., 2001).

HRV Research Contributions

As I was asked to include a discussion regarding how our research has contributed to the general thrust of HRV research and its clinical applications, I will briefly outline a few of our contributions to the field.

We partnered with Dr. Singer in a project that took several years to complete where we recruited confirmed healthy participants and recorded 24-h ambulatory Holter recordings in order to establish normal HRV values and cutoff points for future health risk from ages 9 to 99 (Umetani et al., 1998). This widely referenced paper was the first we know of to establish age-adjusted normative HRV values for clinical risk assessment across a wide age range. We also developed a comprehensive 24-h HRV assessment called the Autonomic Assessment Report and HRV interpretation guide (McCraty & Atkinson, 1996) as a service that we provide to numerous functional-medicine focused clinics. The report provides both time and frequency domain variables and their corresponding normal ranges, 24-h heart rate profile, circadian rhythm analysis of the various HRV frequency ranges and plots of HRV rhythm over the 24-h. This has allowed us to collect 24-h HRV data from thousands of patients with a wide variety of health challenges which has been clinically informative. It was clear that several of the existing interpretations at that time of HRV measures needed further research to clarify. For example, we were among the first to point out that the Low Frequency (LF) band is not a measure of sympathetic activity, and called into question the concept of the LF/HF ratio being an indicator or sympathetic/parasympathetic balance, at least in resting state recordings and especially when doing resonant frequency breathing or HRV coherence training (Tiller et al., 1996).

Another contribution has to do with the Very-Low-Frequency (VLF) Band, which had been largely ignored even though a low VLF rhythm had been established as the most predictive of adverse outcomes (Tsuji et al., 1994). We consistently found that overall, the VLF was at its highest levels during sleep, and peaks just before people wake in the morning. We also found that many reported sleep issues were correlated with the acrophase of the peak of its highest activity level occurring in the middle of the night. New light began to be shed on the primary mechanisms underlying the VLF rhythm after some surprising results from a collaborative study we conducted with Dr. Armour. In this study we analyzed monthly 24-h HRV recordings over a 1-year period of dogs who had undergone auto-transplanted hearts in which there is no need for anti-rejection medications. A surprising finding was that the levels of HRV in the de-innervated hearts was higher than in the control dogs, including rhythms that are associated with respiration, which was sustained over the year (Murphy et al., 2000). This was surprising because there is very little HRV in human transplant recipients (Ramaekers,et al., 1996). This led us to rethink many of our previous assumptions about the mechanisms and interpretations of HRV (McCraty & Shaffer, 2015; Shaffer et al., 2014).

Largely based on my promptings, Dr. Armour developed new recording methods and was able to obtain long-term recordings from single afferent neurons in a beating heart and simultaneously from extrinsic cardiac neurons (Armour, 2003a). It was clear from these recordings that the VLF rhythm was being generated from the intrinsic cardiac nervous system in a context where the recordings could not be influenced by sympathetic activity, movement, etc. However, when he stimulated efferent sympathetic neurons, it elevated the amplitude of the afferent neuron's intrinsic VLF rhythm and could change the frequency of the rhythm. In other words, these findings strongly suggest that the VLF rhythm is produced within the heart itself and that this intrinsic rhythm appears to be fundamental to health and well-being.

Although most discussions of the ANS focus on the efferent (descending) pathways, our observations of the heart rhythms patterns covarying with and reflecting emotional states, led us to explore more deeply the role the afferent (ascending) nerves play in modulating the heart rhythm and thus the coherent state. It is known that 85% to 90% of the nerves in the vagal nerves are afferent and that the cardiovascular system afferents send signals to the brain to a much greater extent than other major organs (Cameron, 2002).

A well-known hypothesis introduced by psychophysiologists John and Beatrice Lacey, called the "baroreceptor hypothesis," identified a causal relationship between the heart's afferent inputs and cognitive performance (Lacey, 1967; Lacey & Lacey, 1974). This work was significantly furthered by Christoph Wölk and Manfred Velden, who identified the importance of the heart rhythm pattern and its stability in influencing neurological functioning (Wölk & Velden, 1989; Wölk et al., 1989). Their primary focus was on micro-scale temporal patterns of cardiac activity occurring within a single cardiac cycle, or, at most, across 3–4 heartbeats (Wölk & Velden, 1987, 1989). However, research in neurocardiology had established that the interactions between the heart and brain are much more complex than previously thought and that neural patterns in afferent activity occur over time scales ranging from milliseconds to minutes. The heart's intrinsic nervous system has both a short-term and long-term memory which affects afferent rhythms related to both mechanical factors (pressure, HR, and rate of change) occurring over milliseconds (single cycles) and activity related to hormonal and mechanical factors that operate over seconds to minutes (Armour & Kember, 2004), (Ardell et al., 2009; Armour, 2003b). This led our research team to postulate that the organization of the heart's rhythmic activity over longer time scales could also have a direct effect on cognitive processes. We called this the Heart Rhythm Coherence Hypothesis (McCraty et al., 2009b). It postulates that the pattern and stability of beat-to-beat changes in heart rate encode information over macroscopic time scales which can influence cognitive performance and emotional experience. Several studies have since indicated that heart rhythm coherence is indeed associated with significant improvements in cognitive performance (Ginsberg, 2010; Lloyd, 2010; McCraty et al., 2009b). Significant improvements have been found in reaction time experiments and more complex domains of cognitive function, including memory and academic performance (Bradley et al., 2010; Ginsberg, 2010; McCraty et al., 2009a, 2009b). One study found that being in a state of coherence for 5-min prior to an auditory discrimination task produced a sixfold greater improvement in performance than the performance fluctuations typically observed within a single cardiac cycle. It also showed the predicted carryover effect of being in the coherence mode on subsequent cognitive performance as well as a significant correlation between participant's heart rhythm coherence and performance (McCraty et al., 2009b).

A key postulate in Wölk and Velden's hypothesis on the mechanism of how the heart's afferent neural activity influences cognitive performance was that the brain's alpha rhythm is synchronized to the heartbeat. Heart-brain synchronization across longer time periods is also an important aspect of The Heart Rhythm Coherence Hypothesis. We, therefore, devised a method to quantify heart–brain synchronization and confirmed that a significant amount of alpha as well as other brain rhythm activity is indeed synchronized to the activity of the heart and the HRV patterns, and that during higher levels of HRV coherence, the synchronized activity between the heart and brain is significantly increased (McCraty et al., 2009b).

Another important aspect of the cardiovascular afferent system which is related to how HRV Biofeedback can facilitate self-regulation, mental health and reset the regulatory systems is informed by the work of the late Dr Karl Pribram. He showed that we establish physiological and behavioral default "set points" or baseline patterns which are maintained within nested feedback loops in the sub-cortical structures. Once a baseline pattern is established, the brain and nervous system strive to maintain a match between current inputs and the baseline reference (Pribram, 2013). Although more complex, and discussed in detail elsewhere (R. McCraty, 2015b), this is similar to how a thermostat in a heating system works, where once a temperature is set, the system strives to maintain it.

Afferent inputs to the brain originate from many organs, and muscles, especially the face. However, the cardiovascular system has more afferent inputs than any other and is the primary source of consistent patterned rhythms (Cameron, 2002). These afferent inputs not only contain mechanosensitive information related to pressure and rate occurring with each heartbeat, but there are also continuous and dynamically changing patterns of afferent activity related to biochemical information from the chemosensory neurons in the heart's tissues which input into the intrinsic cardiac nervous system. The neural activity in the central nucleus of the amygdala is synchronized to the cardiac cycle due to afferent pathways to the amygdala via the Nucleus of Tractus (Frysinger & Harper, 1990; Zhang et al., 1986). Therefore, the HRV patterns in these cardiovascular afferents to the amygdala are important contributors in informing emotional experience and establishing the baseline set points to which the current inputs are then compared (Ventura-Bort et al., 2021). In addition, most of the mechanosensitive afferent neurons that monitor pressure (baroreceptors) and rate are most sensitive to rate of change. Therefore, when in a coherent rhythm, which has a much higher rate of change, there is an increase in both sympathetic and vagal afferent pathways (Armour, 1991).

To quote Pribram, "Cardiovascular feedback constitutes, by the nature of its diffuse afferent organization, a major source of input to the brain's biasing mechanism; it is an input which can do much to determine set-point. Cardiovascular events are repetitiously redundant in the history of the organism leading to stable habituations. Thus, cardiovascular afferent autonomic activity makes up a large share of the stable base-line from which the organism's reactions can take off" (Pribram & Melges, 1969). When the current inputs (HRV patterns) match one of our previously established neural programs, they are recognized as familiar by the brain. What is familiar to the brain is what we experience as safe or comfortable (Miller et al., 1960). Importantly, this process occurs even when the previously established baseline pattern is one associated with overwhelm, anxiety, confusion, etc. which occurs when these states are repeated often enough for them to have become established as familiar references. When the neural systems maintaining the baseline reference are unstable, due to trauma, anxiety, stress, chemical stimulants, etc., unsettled emotions and overreactions are more likely to occur. When there is a mismatch between the input neural (HRV) patterns and the familiar reference, a change in activity in the central and autonomic nervous systems is produced alerting us to the current state of the mismatch. This is why for individuals who have formed maladapted baselines, or are not familiar with deeper, slower breathing, can experience discomfort when first practicing HRV biofeedback.

In other words, people can get "stuck" in unhealthy mental, emotional and behavioral response patterns. Without a shift in the underlying baseline, it is exceedingly difficult to sustain emotional or behavioral changes, placing people at risk of living their lives through the automatic filters of unhealthy past familiar experience that they may not even be conscious of.

This brings me to an important aspect of why HRV coherence and resonance frequency breathing biofeedback is effective in helping to improve many aspects of mental health and self-regulatory capacity. Dr Pribram convincingly demonstrated that *changes in the pattern of afferent input has to occur* for the establishment or resetting of a stable baseline or set-point (Pribram, 2013).

When individuals regularly practice shifting into HRV coherence, the patterns of afferent neurological signals change to a more ordered (coherent) and stable pattern, and there is state specific increase in vagal afferent traffic indicated by significantly increased heartbeat evoked potentials (MacKinnon et al., 2013; McCraty et al., 2009b).

The capacity for a series of short periods of coherent HRV to effect long-term functional connectivity in emotion-related networks was demonstrated in a recent study that found daily HRV coherence feedback changed the functional connectivity in emotion-related neural networks, increased resting state low frequency HRV power (an indicator of increased HRV coherence) and increased down-regulation of activity in somatosensory brain regions during an emotion regulation task (Nashiro et al., 2021).

When heart-focused breathing is combined with the self-induction of a positive or calm emotional state, the association between the more coherent rhythm and a calm or positive emotion is reinforced. Through this process, new familiar baselines are established, which the brain then strives to maintain, making it much easier for people to maintain self-directed emotional and behavioral control and stability throughout daily life. The resetting of neural patterns happens gradually, and people are often not aware of the positive changes they have made. Signs of having established a new baseline include increased coherence in resting state HRV recordings (Bradley et al., 2010), maintaining HRV coherence for longer periods of time, being naturally kinder, more patient, less reactive and where self-regulating emotions has become more automatic without consciously using a breathing or self-regulation technique.

We have also investigated HRV in the context of social and global coherence and heart rhythm synchronization between pairs of people (McCraty, 2004, 2015a) and in groups (McCraty, 2017), as well as how HRV can synchronize with the power of the resonant frequencies in Earth's magnetic field (McCraty & Deyhle, 2015; McCraty et al., 2017; Timofejeva et al., 2021). In a recent study of groups located in five countries it was found that being in a more coherent HRV rhythm for fifteen minutes increased synchronization not only among group members in each of the groups, it also increased the HRV synchronization with the Earth's magnetic field over the following 24-h period (Timofejeva et al., 2021).

Social or group coherence relates to couples, leadership teams, families, and groups within larger organizations where there is a stable and harmonious alignment among the relationships allowing for the efficient utilization of energy, flow and communication required for harmony collective action (McCraty, 2017; McCraty & Childre, 2010). The harmonious flow in group dynamics is often related to the spontaneous synchronization between group members. For example, when engaged in conversation, people tend to unconsciously synchronize their movements, postures, vocal pitch and speaking rates. (Hatfield, 1994) and important aspects of their physiology often becomes synchronized (McCraty, 2017). In groups, higher levels of physiological synchronization has been associated with increased conformity (Dong, Dai, & Wyer Jr, 2015), the strengthening of social connections, cooperation and trust (Wiltermuth & Heath, 2009), increased pro-social behavior (Fischer et al., 2013), while on the other hand, during arguments, synchrony decreases (Paxton & Dale, 2013).

Given the high degree of social disharmony that is occurring globally, from my perspective, research that can help facilitate increased social coherence is one of the most important new areas of HRV biofeedback applications. Therefore, we recently introduced the following hypotheses:

“(1) Providing feedback of individual and collective heart rate variability coherence and the degree of heart rhythm synchronization between group members will facilitate increases in the group’s coherence, and heart rhythm synchronization. (2) Training in techniques to increase group coherence and heart rhythm synchronization will correlate with increased pro-social behaviors, such as kindness and cooperation among individuals, improved communication, and decreases in social discord and adversarial interactions. (3) Biomagnetic fields produced by the heart may be a primary mechanism in mediating heart rate variability synchronization among group members.”(McCraty, 2017) (p2)

In order for synchronization to occur, a signal of some type (sound, light, tactile, electromagnetic, or chemical) must link and transfer information among the pairs of group members. Related to the last statement in the above hypothesis, in the early years of our research and prior to having access to magnetocardiogram (MCG) equipment, we were able to measure the heartbeat several feet from the body using a very high impedance electrometer connected to a metal plate, similar to the Copper Wall Experiments that Elmer Green had been conducting at that time (Green et al., 1995). Looking at heart-brain synchronization between pairs of participants separated by a distance of 5-feet we found that participant’s brain waves were able to synchronize to another participant’s heartbeats (McCraty, 2004).

Future Recommendations

There are many unexplored areas for future research in the arena of HRV Biofeedback, for example, research that explores how many daily practice sessions and of what lengths are required for resetting one’s baseline, and for lasting clinical and meaningful behavioral improvements. Are there differences in different clinical conditions, or age?

A new and relatively unexplored area for future research is the exploration of simultaneous feedback of HRV and heart-brain synchronization. Can this be used in biofeedback training sessions to increase heart-brain synchronization? How might it result in improving different aspects of cognitive performance, reduced anxiety, or increased self-regulatory capacity?

Another related area for HRV biofeedback in the context of heart-brain interaction research is examining if participants can learn to increase heartbeat evoked potentials and if so, does it increase self-awareness, reduce stress and anxiety and result in changes in functional neural connectivity?

A few studies have examined HRV coherence during sleep and stages of sleep (Burch et al., 2018; Celka et al., 2020; Mateos-Salgado et al., 2022; Trousselard et al., 2014) and HRV biofeedback combined with emotional self-regulation have consistently shown self-reported improvements in sleep (McCraty, 2016). Celka has suggested that the HRV coherence measure during sleep may provide a new and more accurate indicator of sleep quality and the effects of over-training. This is an intriguing idea that needs additional studies.

As I stated earlier, I believe one of the most important focus areas for new research utilizing HRV and HRV coherence feedback is the arena of social coherence. HRV can be used to evaluate the physiological aspects of social interactions, group coherence, and HRV synchronization among group members. Research exploring physiological synchronization in group dynamics has been limited as most experiments have had to isolate people from their natural environments, making it difficult to obtain time-synchronized data in real life contexts. HRV allows for a practical approach for assessing ANS dynamics, stress and emotional states, and assessing pairwise synchronization among group participants in real-time. There are many research opportunities for exploring HRV biofeedback and various techniques, exercises and processes for increasing group coherence and synchronization and if and how this is associated with increased group performance, pro-social behaviors, cooperation and improved communication.

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