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SPECIAL ISSUE

Heart Rate Variability Biofeedback, Self-Regulation, and Severe Brain Injury

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This article describes a study using heart rate variability (HRV) biofeedback to treat emotional dysregulation in 13 individuals with severe chronic brain injury. Measures included HRV indices, tests of attention and problem solving, and informant reports of behavioral regulation. Results demonstrated that individuals with severe brain injury were able to learn HRV biofeedback and increase coherence between the parasympathetic and sympathetic nervous systems. Individuals who attained the greatest coherence were rated as being able to best regulate their emotions and behavior.

Case Example: Whatever Happened to Aaron Greene?

Aaron Green was a 41-year-old man who was hit by a car while returning home from a run. Rushed to the emergency room, Aaron remained in a coma for 1 week. After regaining consciousness, Aaron stayed as an inpatient for 2 months before being transferred to a rehabilitation unit, where he continued for 3 months as an inpatient and 2 years as an outpatient. Before the accident, Aaron worked as a computer technician with a company that services computer terminal failures in banks and the New York Stock Exchange. "I was good, I was the best," Aaron said, "but since my accident, I can't get a job because in interviews they want me to discuss computers and I can't. I am sure I can do it [work in his former capacity], but I don't have the words to discuss it."*

After completing his rehabilitation, Aaron called up his former boss one evening and learned about a job. "Within 30 minutes I got the job. I just had to meet with Sven, the Head of the Department, to make final arrangements." "Were you nervous about going back to work?" I asked Aaron. "Not really, I just wanted to work. I knew everything would be OK."

But Aaron encountered more challenges: While on his way to troubleshoot a problem that one of his company's largest clients, Chase, was having with some of their computer terminals, Aaron describes how his mind went "blank." He knew that Chase was located just seven blocks away, but he couldn't remember how to get there. "I've been to Chase so many times, but suddenly I couldn't remember their address. So I just kept walking, thinking if I saw the building I would recognize it." After walking the streets for 60 minutes, Aaron got a call from his boss. "What the hell is going on, Aaron? Chase just called me up again and told me you had not arrived. Get to Pine and Water Street, 12th floor now!"

Aaron looked at me squarely and confessed, "All these clients, I couldn't even remember their names," he said. "And when I don't remember names I get very nervous. It's a big part of a job."

On disability insurance at the time of initial evaluation, Aaron attended a day program for individuals with brain injury. In the morning, a car picks him up to drive him to the program. He described waking up late one morning and getting ready as quickly as possible. On this particular morning, however, Aaron discovered that not only could he not find his favorite cereal but he was also out of chocolate milk and couldn't locate his house key. Downstairs, the car waited for Aaron, while upstairs, Aaron, who was without breakfast, chocolate milk, and his house keys, angrily emptied the contents of two kitchen drawers and his trash can onto the kitchen floor. "Maybe I threw out my keys last night with the trash," he thought, but unable to find the keys, Aaron decided there was only one thing left to do: Leave without locking his door.

* pseudonym

Like Aaron, many individuals with brain injury are prone to emotional outbursts that impede thinking clearly about a challenge they may face and forming a logical plan/solution to address the situation. Such executive functioning deficits often pose primary challenges to individuals with a brain injury. Executive functions are defined as the ability to self-regulate, inhibit impulses, exercise restraint, focus and sustain attention, draw upon memory, change expectations and behavior, and adapt as needed to changing circumstances (Kennedy et al., 2008; Ylvisaker, Hanks, & Johnson-Greene, 2002). Rehabilitation for these individuals is typically structured much like a classroom, with the patients taking notes and working on homework exercises that teach them how to compensate for lost functional skills. Individuals with severe brain injuries, however, typically lack the prerequisite verbal and organizational skills necessary to benefit from these intervention methods.

To counter this problem, research has begun to address poor self-regulation, through an intervention that relies on heart rate variability (HRV) biofeedback. This psychophysiological approach has the potential to improve the functional behavior of individuals with severe brain injury by increasing their home, work, and social integration. In addition, this approach may also lead to a paradigm shift from cognitive rehabilitation to psychophysiological rehabilitation for this difficult-to-treat population. HRV is quantified by measuring the RR intervals—the time between successive heartbeats (also referred to as R-wave peaks). Many physical and psychological factors influence the variation in RR intervals. Respiratory sinus arrhythmia (RSA) refers to the component of change in RR intervals that is synchronized to our breathing cycle. RSA may be a dominant component of the change in the RR interval when the individual's breathing is at an optimal frequency, which is referred to as resonant frequency (Lehrer, Vaschillo, & Vaschillo, 2000) and is also referred to as coherence (McCraty, Atkinson, Tomasino, & Bradley, 2009). The amplitude of RSA tends to be reduced in people with emotional disorders. Further, low HRV has been associated with panic symptoms, depression, poor attentional control, emotional dysregulation, and inflexibility of behavior (Baguley, Nott, Slewa-Younan, Heriseanu, & Perkes, 2009; Gorman & Sloan, 2000; Karavidas et al., 2007; Lehrer et al., 2000; Lehrer, Sasaki, & Saito, 1999; Lehrer & Vaschillo, 1999; Porges, 2001; Wilhelm, Trabert, & Roth, 2001). From both an emotional and physical standpoint (Porges, 2001; Thayer, Hansen, Saus-Rose, & Johnsen, 2009), RSA has been shown to be most closely associated with the ability to self-regulate, such that individuals with brain injury and impaired self-regulation often display HRV patterns with reduced HRV. These associations suggest that HRV treatments, which increase the influence of RSA and enhance the variation in RR intervals, could directly enhance the ability to self-regulate.

Table. Participant injury characteristics, etiology, and work history

Variable	***n***
Loss of consciousness[a]	
Not traumatic brain injury (TBI), not applicable	5
1–4 wk (severe)	2
4 wk + (severe)	4
Not available in medical record	2
TBI	
MVA	6
Fall	1
Assault	1
Not TBI	
Aneurysm	1
Anoxia (at birth)	1
Ataxia, cerebral palsy, progressive dementia	2
Brain tumor	2
Lawyer	1
Salesman	1
College student	1
No work experience	10

[a]Loss-of-consciousness classification (Kraus, 1999).

Our current study had two goals: (a) to determine if individuals with severe, chronic brain injury can modify HRV through biofeedback and (b) to determine if improved HRV coherence is associated with improved self-regulation.

Method

Thirteen individuals were recruited from a community-based structured day program in New York City that provides long-term rehabilitation services for individuals with moderate-to-severe brain injury. The Table has descriptive information on this sample.

Our study featured a single-treatment, nonrandomized, unblinded quasi-experimental design with testing repeated at three time points: pretreatment test (Time 1 [T1]), pretreatment test (Time 2 [T2]), and posttreatment test (Time 3 [T3]). The two pretreatment testings (T1 and T2) served as the baseline against which the posttreatment scores were compared and served to control for the effects of time and practice. Testing at each time point included 5 to 6 hours of neuropsychological testing and completion of self-and informant reports. Recordings of the participants' HRV for Times 1, 2, and 3 were measured during separate sessions, within 2 days of neuropsychological testing. Following baseline testing, the participants received the HRV biofeedback sessions. The participants were paid $10 for participating in each 5- to 6-hour testing session, $5 for completing additional questionnaires after treatment ended, and $5 for each individual treatment session. During the individual treatment sessions (see below), they also received $5 extra for attaining biofeedback "reward cycles" (bells chime when the individual is able to achieve high coherence) using a portable HRV biofeedback device, referred to as a "handheld" (emWave®2 developed by HeartMath Inc.), which they took home for practice.

Measures

Tests that measure two primary components of executive function were administered: (a) Problem Solving: Category Test (Reitan & Wolfson, 1993) and (b) Attention: Integrated Visual and Auditory Continuous Performance test (IVA+Plus CPT; Sanford & Turner, 1995). We also administered a global test of cognition to derive a single "Impairment Index" (Reitan, & Wolfson, 1993). The participants completed a self-report that assessed their perceptions of their executive functioning (the Behavioral Rating Inventory of Executive Functioning, self-report version [BRIEF-A]; Roth, Isquith, & Gioa, 2005). The informants completed the informant version of the BRIEF-A to capture the informant's views of the participants' executive functioning in real life. Six participants had program staff as their informants, and seven had family members as informants. Two additional questionnaires were added to the study at posttreatment testing: Satisfaction With Life Scale (SWLS; Diener, Emmons, Larsen, & Griffin, 1985) and the Rosenberg Self-Esteem Scale (RSES; Rosenberg, 1965).

After the participants completed their neuropsychological testing, their HRV was recorded. HRV in the form of RR interval tachograms was measured with the use of an infrared plethysmograph sensor. For both HRV training with biofeedback and for HRV recording during pre- and posttreatment testing, the emWave® PC (HeartMath Inc.) was used. A sensor was placed on either the left or right earlobe. HRV recordings were obtained over a 10-minute period, which was divided into two 5-minute epochs; no visual or auditory feedback was provided during the HRV recording. In accordance with HeartMath's standard procedure (R. McCraty, personal communication, March 9, 2009), for the purposes of collecting data of the participants' HRV at pre- and posttreatment testing, the following script was read to the participants:

For 10 minutes, I would like you to sit quietly with your eyes open, kind of like you are waiting at a bus stop for the bus. Please avoid using any relaxation techniques such as meditation. Also avoid any intense mental activity. I will let you know when the 10 minutes are up.

Frequency domain variables were calculated using nonparametric power spectral density (PSD) analysis. Two frequency measures of HRV coherence were used as outcomes: (a) low-frequency power (LF)/high-frequency power (HF; 0.04–0.15 Hz)/(0.15–0.4 Hz) and (b) the coherence ratio (McCraty et al., 2009). Coherence ratio is defined by the proprietor of the biofeedback equipment (HeartMath) as Peak Power/Total Power − Peak Power. Peak power was defined as the integral of the PSD in a 0.03-wide window centered at the maximal PSD value located between 0.04 and 0.26 Hz. Total power encompassed the frequency range of 0.003 to 0.5. For the purposes of this study, to limit the coherence ratio between 0 and 1, the ratio was modified into an easy-to-interpret scale that varied from 0 (no coherence) to 1 (total coherence), thereby creating a "normalized" version of HeartMath's coherence ratio, defined as Peak Power/Total Power. Higher ratios (both LF/HF and coherence ratio) indicate greater coherence (Jovanov, 2008; McCraty et al., 2009).

Treatment

HRV biofeedback training was conducted with the HeartMath emWave® PC and the Thought Technology Ltd. Procomp Infiniti, with the Biograph Infiniti software. Ten weekly 1-hour individual sessions were conducted at the day program in a private office, consisting of four elements: (a) Education (how stress can be pictured in heart rate

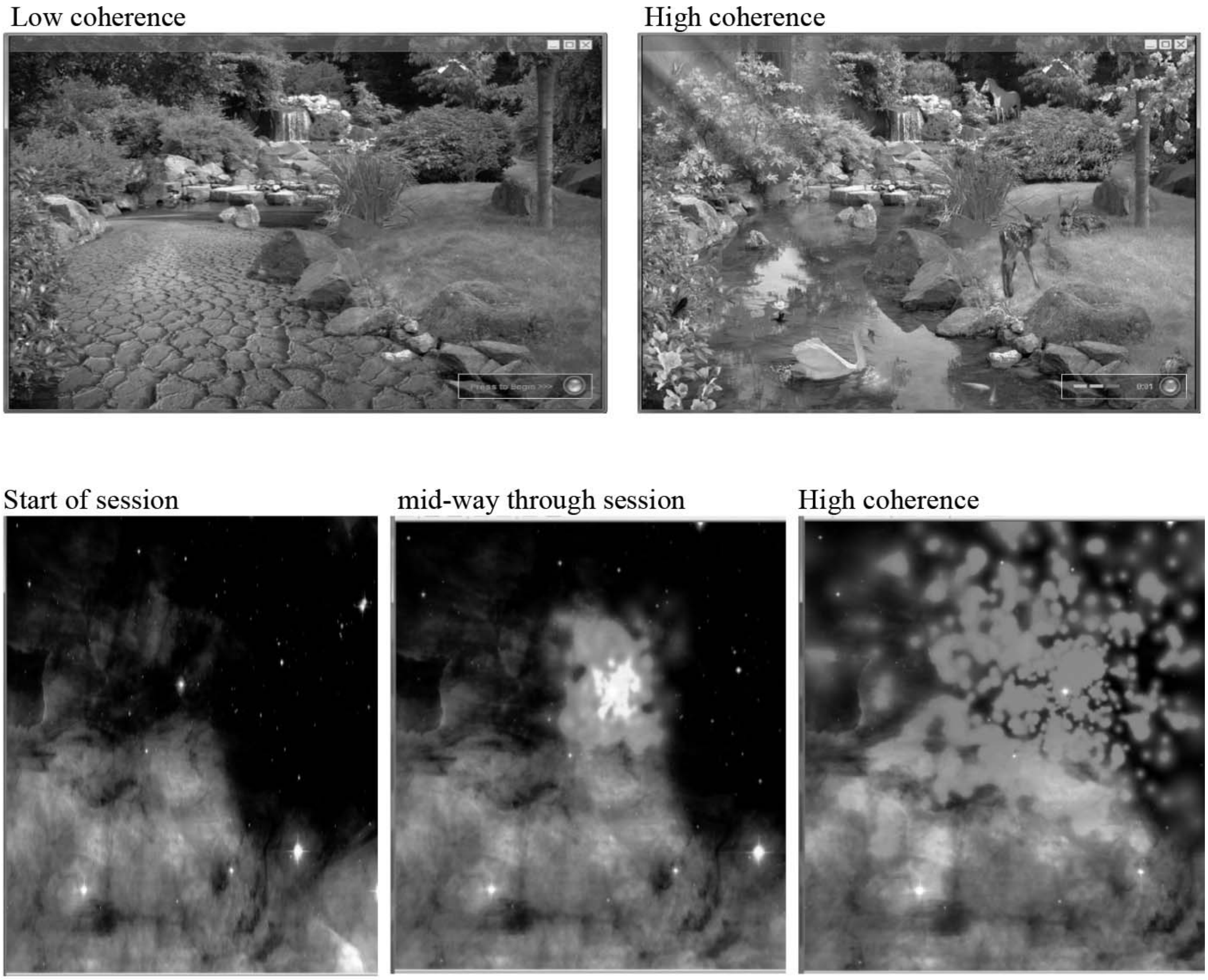

Figure 1. Heart rate variability biofeedback: garden game and emotion visualizer. Garden game: The first picture (top row) represents the screen that appears at the start of the session. The last picture represents how the screen is transformed once the individual achieves coherence. Emotion visualizer: The first picture (bottom row) represents the screen that appears at the start of the session. The subsequent pictures represent how the screen is transformed once the individual achieves coherence.

patterns); participants were provided with a picture of ideal HRV (heart tracing). (b) Breathing pacer training to train participants to increase peak-valley amplitude of HRV waves. Slow breathing at 4.5 to 6.5 breaths per minute maximizes the peak-valley amplitude of HRV waves (Lehrer et al., 2000; McCraty et al., 2009). Connected to HRV biofeedback equipment, participants saw their heart tracing on a computer monitor in real time and also received auditory feedback as they tried to reproduce the picture of the ideal HRV (the heart tracing). For a portion of this breathing pacer training, the BioGraph RSA training program was also used. The BioGraph ECG sensor is a preamplified electrocardiographic (ECG) sensor for directly measuring the heart's electrical activity. ECG sensors were attached to both the left and right wrist of the participant with adhesive tape. The participant also wore a girth sensor wrapped over clothing around the participant's abdominal area with a self-adhering belt. This sensor detected abdominal expansion and contraction and showed the respiratory waveform and amplitude. (c) HRV interactive game. Played without guidance of a breathing pacer or the additional sensory cue provided by a girth sensor (belt), treatment sessions also involved the HeartMath interactive game of choice (see Figure 1). The games are programmed

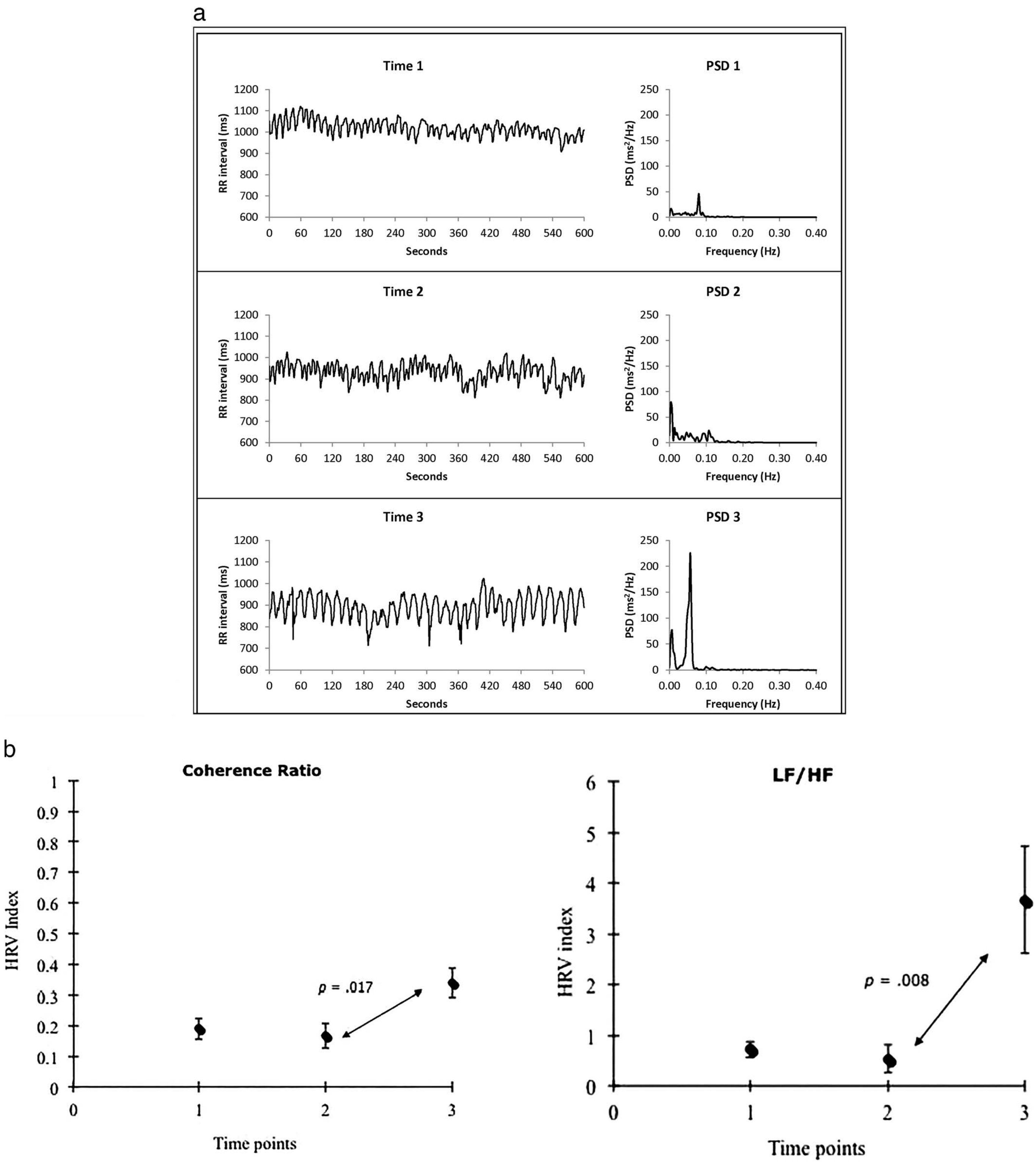

Figure 2. (a) Representative data of heart rhythm pattern changes across time—pretreatment to posttreatment—from a single participant. (b) Heart rate variability recording at pretreatment (T1 and Time 2) and posttreatment (Time 3).

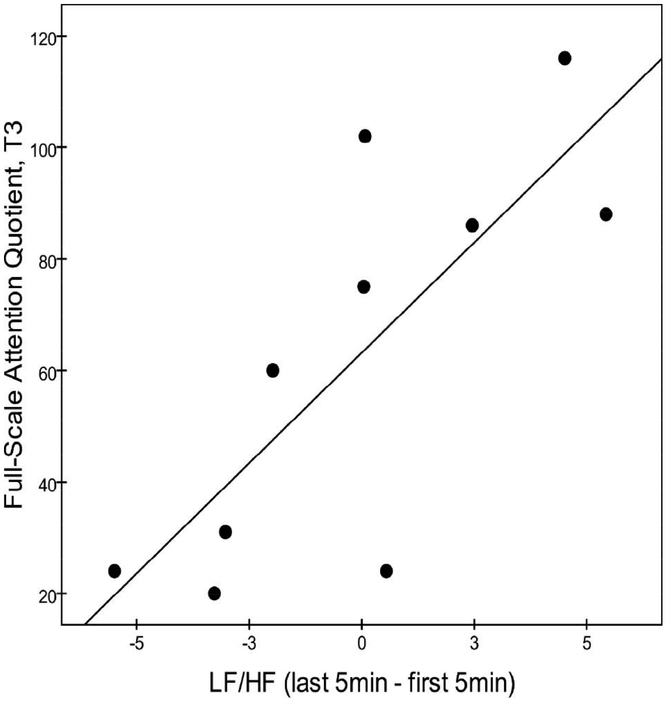

Figure 3. Full-scale attention quotient at Time 3 and low-frequency power/high-frequency power index, the last 5 minutes of the full 10-minute recording taken at Time 3.

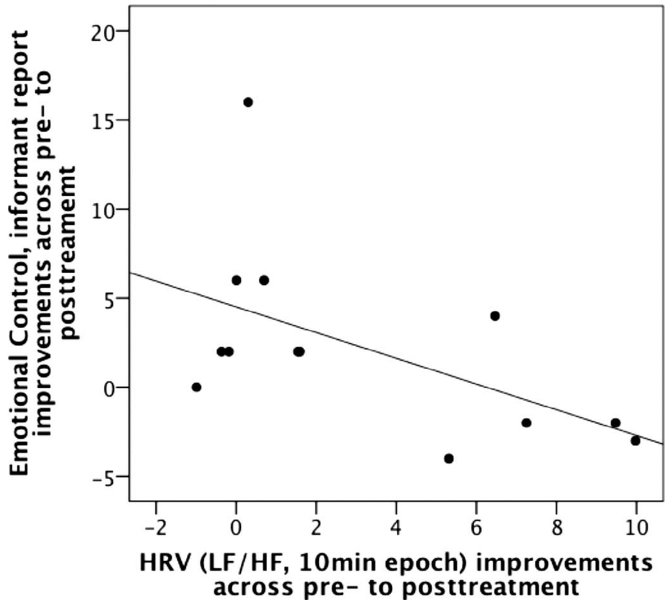

Figure 4. A scatter plot depicting improvements in BRIEF-A emotional control informant ratings versus heart rate variability (low-frequency power/high-frequency power 10-minute epoch) improvements across pre- to posttreatment testing.

to provide positive feedback when HRV becomes optimal. From the fifth session onward, sessions ended with (d) review of assigned home practice with the handheld HRV biofeedback device. At the fifth training session, the participants were given and trained in the use of a handheld HRV biofeedback, a cell-phone sized device, for home practice. It is important to note here that all of the participants in this experiment had a brain injury at the severe range. Thus, they required 4 weeks of closely supervised training in HRV biofeedback before any independent practice with the handheld HRV device could be undertaken. Adherence with home practice, from Session 5 onward, was assessed by the participants demonstrating the ability to operate the handheld device and attain high levels of coherence. The handheld device is programed to chime bells (referred to as "reward cycles") once the individual is able to elevate HRV to high levels of coherence. As an added incentive to practice at home, participants earned a $5 bonus if they achieved a reward cycle during their individual sessions. Finally, for the last 5 weeks of treatment, in addition to their 1-hour individual sessions, each participant also attended a small, semi-supervised 30- to 45-minute meeting at the structured day program where each participant practiced attaining HRV coherence in a group setting.

Results

At posttreatment, as predicted, the participants' HRV measures, both LF/HF and the coherence ratio, increased dramatically from pretreatment to posttreatment testing. Figure 2 displays the HRV improvements.

At posttreatment testing, there was a significant association between IVA-CPT attention and the magnitude of change in the participant's LF/HF index in the last 5 minutes of recording. Participants who increased their LF/HF ratio values during the last 5 minutes of the full 10-minute recording had higher attention scores (see Figure 3).

To test if improvements in emotional control (informant ratings) were related to improvements in HRV (LF/HF index, 10-minute epoch) from pre- to posttreatment testing, a bivariate regression analysis was conducted. The results of this test were significant (the probability that the results occurred due to chance is low; $p = .027$) with a large effect size (the strength or magnitude of the relationship between HRV and emotional control; $r = .547$; see Figure 4).

Improvements from pre- to posttreatment testing in the HRV index (coherence ratio 10-minute epoch) also proved a significant predictor of the participants' self-reports on satisfaction with life (SWLS) and self-esteem (RSES).

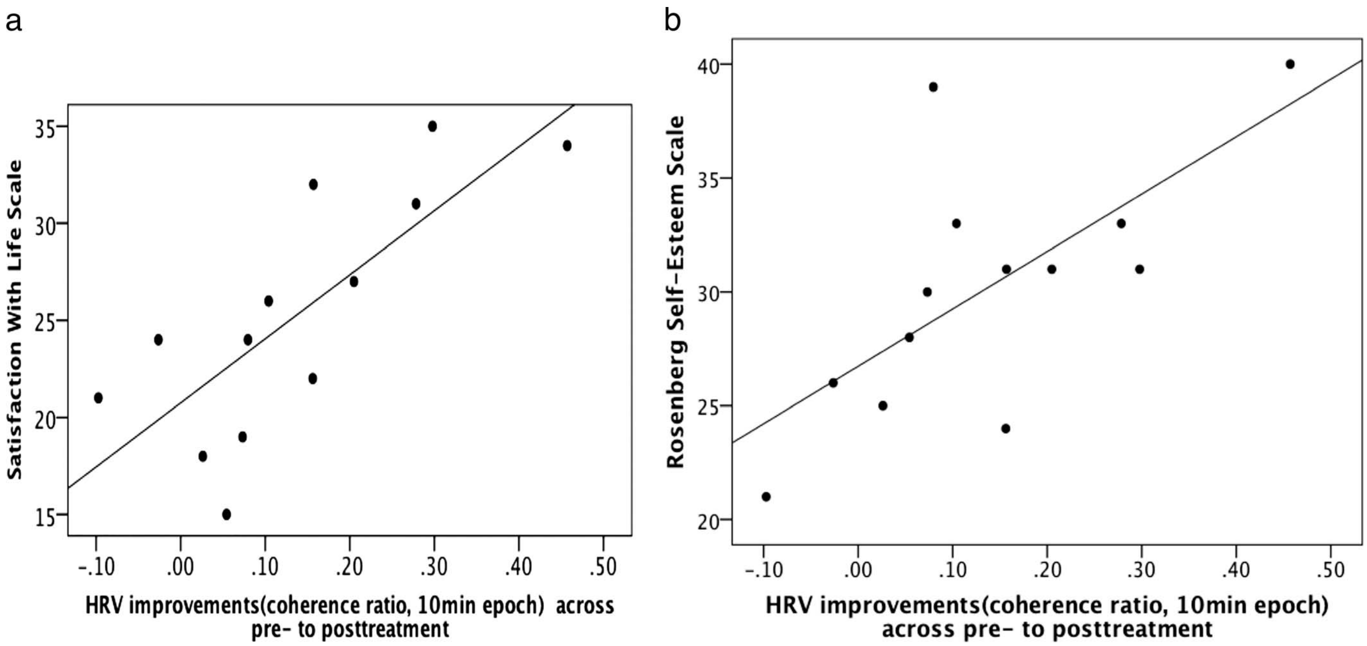

Figure 5. (a) A scatterplot of scores in Satisfaction With Life Scale and heart rate variability (coherence ratio 10-minute epoch) improvements across pre- to posttreatment. (b) A scatterplot of scores on self-esteem (RSES) and HRV resonance.

Greater improvements in HRV were related to participants' reports of higher satisfaction with life as well as higher self-esteem (see Figures 5a and b). These measures were added at posttreatment testing, making it impossible for us to demonstrate that increases in these psychosocial measures were directly related to HRV biofeedback treatment. However, the significant linear relationship with large effect sizes between the variables of interest (HRV and SWLS, HRV and RSES) suggest that HRV biofeedback can have a positive impact on quality-of-life measures—a suggestion that is supported by literature on self-regulation and biofeedback with individuals without neurological disorders (Giardino, Chan, & Borson, 2004; Nolan et al., 2005).

One subscale of the BRIEF-A informant report is designed to rate the individuals' ability to self-monitor while working on a task. An analysis was conducted to compare the informants' ratings on this subscale with the participants' self-ratings. This analysis was conducted with just the seven participants who had family members as their informants. Results indicated that no relationship existed between the families' rating of the participant and the participants' self-rating prior to treatment. After treatment, however, results suggested a significant relation between families' rating and participants' self-rating. Further, how the participants rated themselves at posttreatment testing also correlated with how the families rated the participants at pretreatment testing.

Discussion

This study provides the first demonstration that self-regulation training using HRV biofeedback can be used to enhance cardiovascular coherence in individuals with moderate-to-severe chronic brain injury. Findings elucidate the relation between psychophysiology and neuropsychology. A significant linear association was observed between improvements in HRV coherence and improvements in informants' ratings of the participants' emotional control. In addition, higher attention scores were correlated with higher HRV coherence. That is, as HRV coherence increased during a 10-minute HRV recording session, so did performance on a measure of sustained attention. HRV coherence also predicted scores on life satisfaction and self-esteem. In addition, this experiment suggests that HRV biofeedback may increase self-awareness in individuals with severe brain injury. This result was unexpected. At posttreatment testing, a significant relation emerged between family ratings of how well the participants were able to self-monitor while working on a task and participants' self-rating; in addition, the participants' self-ratings at posttreatment testing correlated strongly with the families' ratings at pretreatment testing. These findings indicate that at posttreatment, the participants' self-rating became more closely aligned to how others (family members in particular) perceived their behavior.

Concluding Remarks

This experiment indicated that HRV biofeedback has promise as an effective, cost-efficient method for improving self-regulation in individuals with severe brain injury. Given these preliminary findings, a study with more experimental manipulation and a control group with an active alternative treatment could provide more information on the mechanisms needed to determine if there is a causal relation between HRV biofeedback and self-regulation and HRV biofeedback and quality-of-life measures. Future studies should further evaluate whether HRV biofeedback training helps to improve the participants' insight into their own behavior and the extent to which any insight leads to better relations with their family members.

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Declaration of Interest

Dr. McCraty is the director of research at the Institute of HeartMath. Dr. Cavallo is the associate director of Adult Day Services at AHRC NYC. Dr. Foley has served on advisory boards for Bayer Healthcare and Biogen Idec, received an investigator research grant from Bayer, and has received honoraria as a speaker from Bayer, Biogen, and Teva Neuroscience. The other authors have no conflicts of interest to disclose.

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