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Heart rate variability biofeedback, executive functioning and chronic brain injury

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Abstract

Primary objective: To determine if individuals with brain injury can modify heart rate variability (HRV) through biofeedback and, if so, enhance its pattern to improve emotional regulation and problem-solving ability.

Design: A quasi-experimental design with repeated measures was employed. Thirteen individuals aged 23–63 years with severe brain injury (13–40 years post-onset) participating in a community-based programme were enrolled.

Main outcomes: Response-to-treatment was measured with HRV indices, Behavior Rating Inventory of Executive Function (BRIEF-A-Informant) and attention/problem-solving tests.

Results: At post-treatment, HRV indices (Low Frequency/High Frequency [LF/HF] and coherence ratio) increased significantly. Increased LF/HF values during the second-half of a 10-minute session were associated with higher attention scores. Participants who scored better (by scoring lower) in informant ratings at pre-treatment had highest HRV scores at post-treatment. Accordingly, at post-treatment, families' ratings of participants' emotional control correlated with HRV indices; staffs' ratings of participants' working memory correlated with participants' HRV indices. Self-ratings of the BRIEF-A Task Monitoring scale at post-treatment correlated with family ratings at pre-treatment and post-treatment.

Conclusions: Results demonstrate an association between regulation of emotions/cognition and HRV training. Individuals with severe, chronic brain injury can modify HRV through biofeedback. Future research should evaluate the efficacy of this approach for modifying behavioural problems.

Keywords: *Heart rate variability (HRV) biofeedback, executive functioning, brain injury*

Introduction

Brain injuries from many sources cause impairments that affect physical, cognitive and psychosocial functioning in individuals of any age [1–3]. Also, deficits in executive functioning present more obstacles to an individual's full return to social functioning than physical or medical complications do [4]. Fundamental to executive functioning is self-regulation, which is a person's ability to inhibit impulses, exercise restraint, adapt as needed and turn passive experience into productive activity [5–9]. A significant deficit in self-regulation is a hallmark of individuals with brain injury [10–13].

Various theories about the underlying constructs of executive functioning have emerged from recent studies in goal management training [11, 12, 14], social problem-solving theory [15–18] and the somatic hypothesis [19–22]. The current study draws on the somatic hypothesis and the application of psychophysiological measures in biofeedback

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training, specifically HRV, which refers to the variation between heartbeats. The relevant literature shows that heart rate variability (HRV) is associated with emotions and thoughts; the literature also shows that self-regulation training that incorporates HRV biofeedback can improve regulation of emotions and behaviour and, in turn, improve cognitive functioning [23–28].

HRV typically is quantified by measuring the interval between successive R-wave peaks (RR intervals) in the electrocardiogram (ECG). Many physical and physiological factors influence the time between RR intervals. Respiratory sinus arrhythmia (RSA) refers to the component of change in RR intervals that is synchronized to the respiratory cycle [29]. 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' [29])—also known as 'coherence'. The goal of HRV biofeedback is to help individuals increase the relative amount of RSA in the HRV signal. From both a psychological and physiological standpoint [27, 30, 31] RSA has been shown to be most closely associated with self-regulation. The amplitude of RSA tends to be reduced in people with emotional disorders; low HRV has been associated with panic symptoms, depression, poor attentional control, emotional dysregulation and inflexibility of behaviour [24, 32, 33]. Recent findings establish a direct connection between the central nervous system (CNS) and the autonomic nervous system (ANS), which is reflected in HRV [27, 34, 35]; and pre-frontal activity has been associated specifically with vagally-mediated HRV [36–40].

It is important to note that the current study relies upon evidence that severe brain injury can cause dysregulation of the ANS [41–45]. More specifically, individuals with brain injury who suffer from autonomic dysfunction typically exhibit little modulation of heart rate and low amplitude in the HRV patterns [41, 46]. These findings of decreased HRV are correlated with an individual's deficits in tasks that involve executive function [35]. For example, Hansen et al. [47] found that individuals with *greater* HRV had significantly more correct responses in a working memory test and in a continuous performance test (CPT). The group with greater HRV also demonstrated faster reaction time than the group with low HRV. Likewise, Mezzacappa et al.'s [48] study of children with emotional and behavioural disorders found that higher scores on tasks requiring executive control—speed in responding, accuracy of response and inhibition of response in relation to changing information—were significantly associated with higher respiratory sinus arrhythmia (RSA). Executive functioning has been associated with large amplitude modulation in HRV [31, 35, 46, 49] and large amplitude modulation in HRV has been referred to as *coherence* or *resonance* [29, 50]. Maximal modulation occurs at a particular 'resonant frequency' of the baroreflex system, typically ~0.1 Hertz or a 10 second rhythm [29]. As it pertains to HRV, resonance is thought to reflect a balance between the two branches (sympathetic and parasympathetic) of the autonomic nervous system (ANS).

In sum, recent evidence indicates that HRV is associated with certain specific executive functions—attention, flexibility of behaviour and control of emotions [27, 31, 47, 48]. Also, Biswas et al. [42] report findings that indicate not only an association between the magnitude of HRV and the severity of head injury, but also an association between the recovery of higher HRV levels and rehabilitation of the injured individual. These associations suggest that modulation of both efferent and afferent ANS activity through HRV training could enhance the prefrontal cortex's role in executive functioning and in the individual's ability to self-regulate emotional responses and behaviour.

With these recent findings in mind, the current study had two goals: (1) to determine if individuals with severe, chronic brain injury can modify HRV through biofeedback training; and (2) to determine if improved HRV coherence in these individuals is associated with improved emotional regulation and problem-solving ability.

Method

Participants

Participants were drawn from a metropolitan brain injury programme, AHRC, in New York City. AHRC is a community-based, structured day programme that provides long-term rehabilitation services for individuals with moderate-to-severe brain injury. This study included 13 individuals with severe brain injury (as documented by prior neuropsychological and neurological evaluations). This experiment was a study of the 'real world' and thus the exclusion criteria employed were minimal and flexible. Table I contains information on the participants' injury characteristics (i.e. severity and cause) and work history. Given the small sample size of this study, medians and interquartile ranges (*IQR*) will be reported. The group consisted of seven men and six women (seven were White, five Black and one White-Hispanic) with a median age of 44 years ($IQR = 22$). The median age of onset was 13 ($IQR = 13$). Median years since the participant's brain injury was 23 ($IQR = 17.5$). Median Full Scale IQ (FSIQ) score was 62 ($IQR = 14.5$). Verbal IQ

Table I. Injury characteristics, aetiology and work history.

Variable	*n*
Loss of consciousness[a]	
Not TBI–not applicable	5
1–4 weeks (severe)	2
4 weeks+ (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	1
Brain tumour	2
Lawyer	1
Salesman	1
College student	1
No work experience	10

[a]Loss-of-consciousness classification [51].

(VIQ) median score was 66.0 ($IQR = 15.75$). Performance IQ (PIQ) median was 64 ($IQR = 10.5$). Median years of education was 12 ($IQR = 2$). Their Halstead Reitan Impairment index median was 1.00 ($IQR = 0.10$). This score indicates that the participants as a group were functioning in the significantly impaired range. As can be seen in Table I, for participants with a TBI whose records were available for review, all of them ranked as severe, according to a conventional classification system [51].

Measures

Impairment index. The following tests were administered to obtain the Impairment Index: Finger Tapping Test, Tactual Performance Test, Seashore Rhythm Test, Speech Sound Perception Test and the Category Test. The Impairment Index is computed from the five tests originally included in the Halstead-Reitan Battery and have been shown to be very sensitive to cerebral damage [52, 53].

Problem-solving. Halstead Category Test (HCT) measures an individual's abstraction or concept-formation ability, flexibility in the face of complex and novel problem-solving and capacity to learn from experience [53]; it has been found to have significant association with problem-solving skills [54, 55]. This test is well-established and validated with good test–re-test reliability [56–58]. A score of 51 errors and above constitutes impairment. The original slide-projector version of the Category Test was used in this experiment.

Attention. The Integrated Visual and Auditory Continuous Performance Test (IVA + Plus CPT) combines visual and auditory stimuli to examine the level of impulsivity, inattention and hyperactivity in individuals from age 6–96; it produces quotient scores for impulsivity and inattention and has been found to discriminate individuals with attention disorders from those without. Test–re-test with a time interval of 1–4 weeks was found to have good reliability ($r = 0.74$, $p = 0.01$) [59]. The primary score used for this study was the Full Scale Attention Quotient (FAQ).

Self-reports and informant reports. A well-established instrument, the Behavior Rating Inventory of Executive Function-Adult Version (BRIEF-A), is a self-report and informant-report measure that captures individuals' views of their own executive functioning as well as their informants' views (see Roth et al. [60] for scoring information and psychometric properties). At Time 1 (pre-treatment), only the self-report version of the inventory was used. At Time 2 (pre-treatment) and Time 3 (post-treatment), the participants and their informants completed this inventory.

Heart rate variability (HRV)—Electrophysiological recording and analysis

After the participants completed their neuropsychological testing, their HRV was recorded. To ensure that fatigue did not confound the signals obtained, this recording usually was made on a different day or after a lunch break. For HRV biofeedback, HeartMath's emWave PC was used. HRV in the form of RR interval tachograms was measured with the use of an infrared plethysmograph sensor. The sensor was placed on either the left or right earlobe, while a computer monitor displayed the individual's HRV patterns in real time.

The Task Force of the European Society of Cardiology and the North American Society of Pacing Electrophysiology [30] established standards for HRV recording and measurement. Frequency-domain variables were calculated using non-parametric power spectral density (PSD) analysis (PSA) of 5-minute-long recordings of the RR intervals. In the current study, however, HRV recordings were obtained over a 10-minute period, which was divided into 5-minute epochs. This longer and divided recording period was chosen for several reasons. It is important to note that this study was novel in at least two respects: HRV biofeedback is

still in the initial stages of being used in neuropsychological testing and its use with a population like the one in the current study is apparently unprecedented. The 10-minute recording period offered a chance to determine to what extent a longer duration of recording could affect the performance of individuals with severe brain injury. It was possible that individuals with greater cognitive impairments would need more time to grasp and implement the HRV biofeedback strategies that were being learned for the first time in treatment. Furthermore, dividing the 10-minute period into two 5-minute epochs offered the chance to determine whether individual performance changed over time, from the first 5-minute epoch to the second one. Frequency bands were set according to the Task Force [30] and they are defined below.

Outliers from the RR intervals were removed when they exceeded the local median value by more than 200 milliseconds. One-sided power spectral densities (PSD) were obtained using the Welch method implemented in Matlab R2008b (The Mathworks, Nattick, MA). A window size of 64 seconds and a 50% overlap was used. Spline fitting was used for integration of the PSD. PSA provides information on how the strength of HRV is distributed as a function of frequency. HRV signals are defined by the following three frequency bands: High frequency [HF] (0.15–0.4 Hz), low frequency [LF] (0.04–0.15 Hz) and very low frequency [VLF] ($\leq$0.04). The total power (TP) includes frequencies from 0.0033–0.4 Hz [30].

A relatively simple custom-made, in-house code was written using Matlab R2008b (The Mathworks, Nattick, MA). Given the recording period of 5 minutes, frequency resolution was ~0.0033 Hz. There are two distinct sampling rates: One to sample the raw signal for electrocardiographic (ECG) signal and one to sample the RR-interval signal. The sampling for this study was 250 Hz and 1 Hz, respectively. These sampling rates are in accordance with the Nyquist criterion for each type of signal [30]. Integration of the power spectrum was performed by first using a splining procedure to fit the smooth curve through the data. Then, following the recommendations set forth by the Task Force, power was calculated for each frequency band: VLF, LF, HF and the three power values were summed to obtain total power.

Two measures of resonance were used in the current study: (1) ratio of the power of the LF band to the power in the HF band (LF/HF), where higher ratios indicate greater resonance [61]; and (2) coherence ratio defined as peak power/total power, where peak power was defined as the integral of the PSD in a 0.03-wide window centred at the maximal PSD value located between 0.04–0.26 Hz [50].

Procedures

All procedures were conducted in compliance with the American Psychological Association's (APA) *Ethical Principles in the Conduct of Research with Human Participants* [62]. The Albert Einstein College of Medicine of Yeshiva University's Institutional Review Board and the AHRC Institutional Review Board both approved the study. An informed consent form was read and signed by all potential participants. Where applicable, a signed Authorization to Use or Disclose Protected Heath Information for a Research Study form was obtained from the participants' 'advocate'.

This study featured a single-treatment, non-randomized, unblinded quasi-experimental design with measures repeated at three time points: Pre-treatment test (Time 1), pre-treatment test (Time 2) and a post-treatment test (Time 3). In this design, the two pre-treatment times served as baselines against which the post-treatment scores were compared and served to control for the effects of time and practice. Testing at each time point included 5–6 hours of neuropsychological testing and completion of self-reports. Informants completed reports and questionnaires on the participants at Times 2 and 3. Recording of the participants' HRV for Times 1, 2 and 3 was done during separate sessions, within 2 days of neuropsychological testing. Times 1 and 2 were separated by a 10-week waiting period. Following baseline testing, the participants received the specially tailored HRV biofeedback sessions. The participants were paid $10 for participating in each 5–6 hour testing session, $5 for completing additional questionnaires after treatment ended and $5 for each individual session. They also received $5 extra for attaining biofeedback 'reward cycles' using a portable cell-phone-size HRV biofeedback gadget, referred to as a 'handheld', which they took home for practice. For the purposes of this paper, only measures listed above were analysed.

Data were collected by a doctoral student trained in neuropsychological evaluations and in HRV biofeedback. The student completed a certification course on HeartMath HRV intervention and, during the period when the intervention was delivered to the participants, she received weekly supervision from HeartMath's Medical Director.

Treatment

HRV biofeedback training was done with HeartMath emWave PC and Thought Technology Ltd. BioGraph Infiniti. The emWave PC hardware/software system monitors and displays an

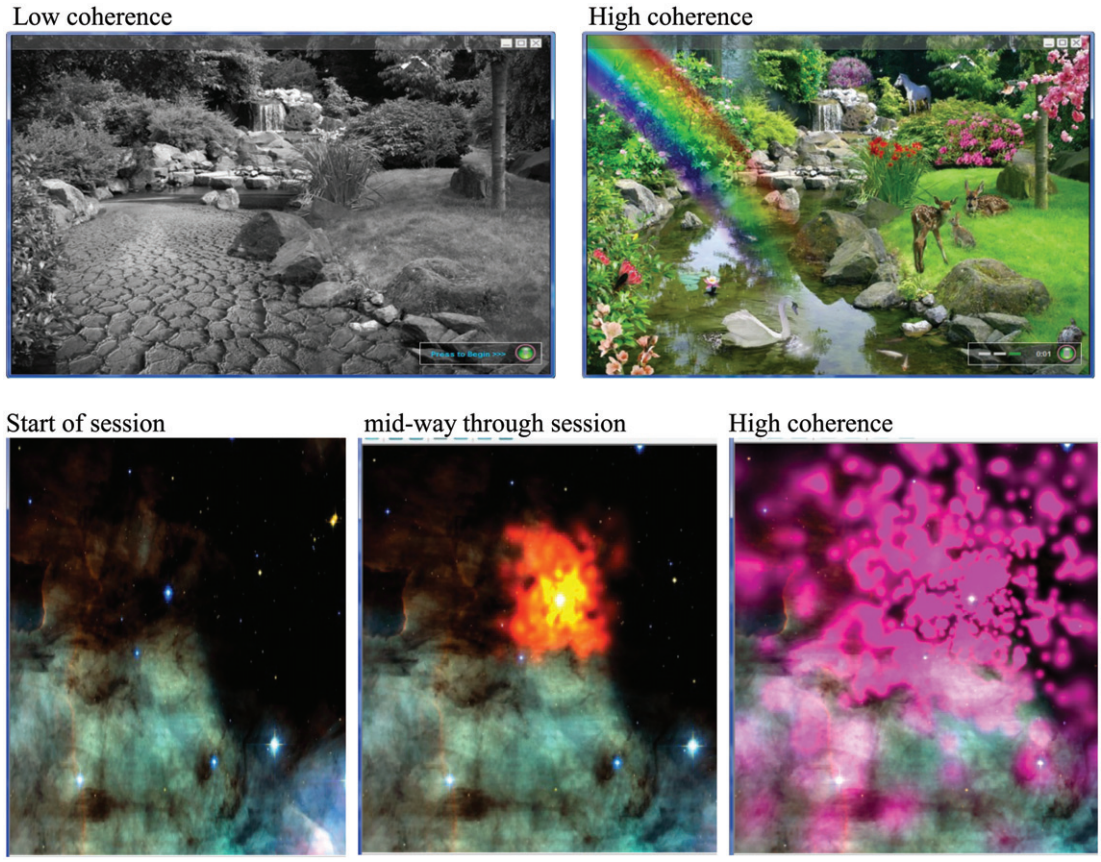

Figure 1. Garden game and emotion visualizer. Garden Game: The first picture (top row) represents the screen that appears at the start of the session. The last picture represents how the screen is transformed once the individual achieves coherence. Emotion Visualizer: The first picture (bottom row) represents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

individual's HRV pattern in real time. Using a fingertip or earlobe sensor to record the pulse wave, this program plots changes in heart rate on a beat-to-beat basis.

The BioGraph RSA training programme was used to provide further training in paced breathing. The BioGraph ECG sensor is a pre-amplified electrocardiographic 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. The amplitude of RSA waves tends to be depressed in people with emotional disorders. Slow breathing at ~0.1 Hz or six breathes per minute ('resonant frequency') increases HRV, produces large oscillations in heart rate and improves pulmonary function [25, 63–65]. Such increases yield increases in the amplitude of the baroreflex and this exercise of the baroreflex can ultimately yield greater reflex efficiency and hence greater modulation of autonomic activity [63].

The treatment scripts were designed on the basis of multiple sources of published manuals [29, 66, 67]. Ten 60-minute individual sessions were provided which included a breathing pacer set at six breaths per minute to train the participants to increase their RSA [64, 65]. Treatment sessions also involved using a HeartMath interactive game of choice (see Figure 1). After four biofeedback treatment sessions, the participants were given the handheld biofeedback devices—cell-phone-size biofeedback gadgets (handhelds)—for home practice.

Statistical analyses

Linear relations among the variables of interest were explored using Pearson's correlation coefficient (r). Neuropsychological test scores and HRV biofeedback scores were evaluated over time using repeated-measures ANOVAs. To aid in the interpretation of the results, effect sizes based on partial eta-squared (η_p^2) were calculated.

To evaluate the association between HRV indices and behavioural measures as reported by the participants' informant ratings, the participants were first split into two groups according to the type of informant (family or staff). This splitting was done because the literature indicates that observations by informants are influenced by their relationships with the individuals of interest [68, 69] and it is shown below that this difference in relationship had an effect on the association with HRV indices. An ANOVA was applied to test for a significant difference between the two groups. Second, given this small sample pilot study, exploratory analyses were conducted to identify measures of interest. Correlation matrices (based on Pearson's r) with BRIEF-Informant scores and HRV indices were examined. Bivariate linear regression analyses were performed to assess the predictive power of various neuropsychological measures on each of the two HRV outcome measures.

Results

Baseline comparisons between the two sub-groups

A Mann-Whitney U-test was conducted to assess group differences—participants with family as informants vs participants with staff as informants. Results demonstrated that there were no differences between the two sub-groups of participants in age, $U = 9.50$, $z = -1.65$, $p = 0.101$, years post-injury, $U = 14.50$, $z = -0.93$, $p = 0.366$, and years of education, $U = 12.00$, $z = -1.47$, $p = 0.234$. In addition, there were no differences in pre-treatment performance in the Category Test, $U = 17.00$, $z = -0.57$, $p = 0.628$, the BRIEF informant ratings (Emotional Control: $U = 15.00$, $z = -0.86$, $p = 0.445$, Working Memory: $U = 12.00$, $z = -1.29$, $p = 0.234$, Task Monitoring: $U = 9.00$, $z = -1.72$, $p = 0.101$) and HRV indices (LF/HF: $U = 20.00$, $z = -0.14$, $p = 0.945$; coherence ratio: $U = 12.00$, $z = -1.29$, $p = 0.234$).

HRV indices and biofeedback training

The results of the multivariate test indicate an overall significant time effect for both LF/HF and coherence ratio [LF/HF: Wilks's Lambda $(\Lambda) = 0.45$, $F(2, 11 = 6.77)$, $p = 0.012$, $(\eta_p^2 = 0.552]$; [coherence: Wilks's $\Lambda = 0.34$, $F(2, 11 = 10.81)$, $p = 0.003$, $(\eta_p^2 = 0.663]$. According to tests of within-subject contrasts, as predicted, both LF/HF and the coherence ratio measures were found to yield a significant effect size (η_p^2) with training (slightly larger effect with the LF/HF ratio: $F(1, 12) = 9.88$, $p = 0.008$ $(\eta_p^2 = 0.452$ [Time 2–Time 3] vs coherence ratio: $F(1, 12) = 7.68$, $p = 0.017$ $(\eta_p^2 = 0.390$ [Time 2–Time 3]). Both measures increased dramatically from pre-training (Time 1 and Time 2) to post-training (Time 3) assessments. Neither LF/HF ratio nor the coherence ratio measure changed significantly from Time 1 to Time 2, LF/HF: $p = 0.458$; coherence ratio: $p = 0.308$. Figure 2 displays the HRV improvements across the three time points, pre-treatment Time 1 and 2 to post-treatment Time 3. Table II shows the descriptive statistics for the participant's HRV indices.

Association between HRV and BRIEF-A informant scores

The informants' (family and staff) pre-treatment ratings of the participants' behavioural control (BRIEF-A) predicted the participants' HRV indices at post-treatment. Although no statistically or clinically meaningful change was observed in the BRIEF scores across pre-treatments (Time 1 and 2) and post-treatment (Time 3), the informants' rating of the participants' executive functioning was significantly associated with HRV scores at post-treatment (Time 3). Pearson's r results showed that the families' rating of the participants' self-regulating ability—emotional control sub-scale—was correlated significantly with moderate-to-large coefficients with HRV indices both LF/HF ratio and coherence ratio, at Time 3: Emotional control and LF/HF: $r(5) = -0.98$, $p = 0.001$; emotional control and coherence ratio: $r(5) = -0.91$, $p = 0.005$. With respect to the staffs' scores, the working memory BRIEF sub-scale at Time 3 was significantly correlated with the HRV indices: Working memory and LF/HF: $r(4) = -0.94$, $p = 0.005$; working memory and coherence ratio $r(4) = -0.86$, $p = 0.028$. There were no significant correlations between HRV and informant ratings in pre-treatment testing. Scatterplots in Figures 3–6 illustrate a strong linear relation among the variables of interest (HRV indices and informant scores on the participant's self-regulation of behaviour).

Association between HRV indices and neuropsychological outcome measures

HRV and category test. A linear regression analysis showed that Category Test scores predicted which participants would improve on HRV biofeedback as measured by the LF/HF index. No statistically or clinically meaningful change was observed in the neuropsychological measures from pre-treatment testing (Time 1 and Time 2) to post-treatment testing (Time 3). The scatterplot (Figure 7), however, indicates that the two variables are linearly related such that the participants with the fewest errors in the Category Test (Time 2) benefitted most from HRV biofeedback and made the greatest improvements at Time 3: $F(1, 11) = 12.41$,

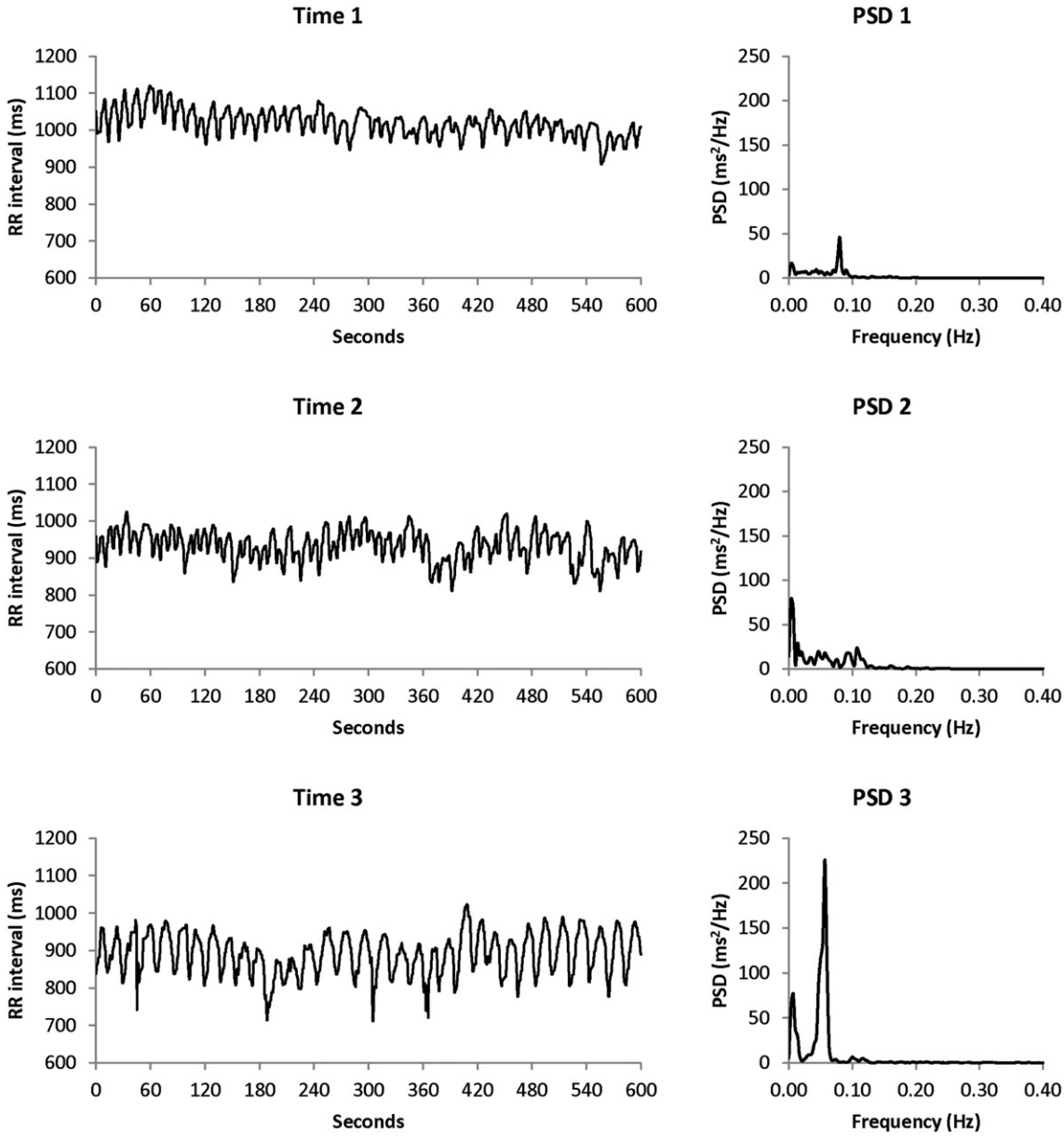

Figure 2. Representative data of heart rhythm pattern changes across time—pre-treatment to post-treatment—from a single participant. Notably, it is only at Time 3 that the participant's HRV displays high amplitude rhythmic oscillations, which are characteristic of strong coherence. Evidence indicates that increasing the amplitude of HRV rhythms strengthens the reflexes that regulate the autonomic nervous system (ANS); and a better-regulated ANS in turn improves the individual's ability to regulate emotions and adapt to his or her changing environment [27, 29–31, 64]. The corresponding power spectral density (PSD) graph shows the highest peak in Time 3 at the particular resonance frequency for that individual to be centred at ~0.1 Hz., providing further confirmation to Vaschillo et al.'s [64] findings that the cardiovascular system (CVS) has the property of resonance at a frequency near 0.1 Hz.

Table II. Medians and interquartile ranges (*IQR*) of HRV scores.

	Time 1		Time 2		Time 3		
	Mdn	*IQR*	Mdn	*IQR*	Mdn	*IQR*	*p-values*
LF/HF	0.71	0.74	0.53	0.86	3.67	6.8	Time 1 to 2 = 0.458 Time 2 to 3 = 0.008
Coherence ratio	0.19	0.08	0.17	0.12	0.34	0.29	Time 1 to 2 = 0.308 Time 2 to 3 = 0.017

LF/HF is the ratio of the power in the low frequency band (0.04–0.15 Hz) to the power in the high frequency band (0.15–0.5 Hz). Coherence ratio is defined as peak power/total power, where peak power is the power within a 0.03 Hz interval centred about the maximum value located between 0.04–0.26 Hz and total power is the power contained within the 0.0033–0.4 Hz frequency range.

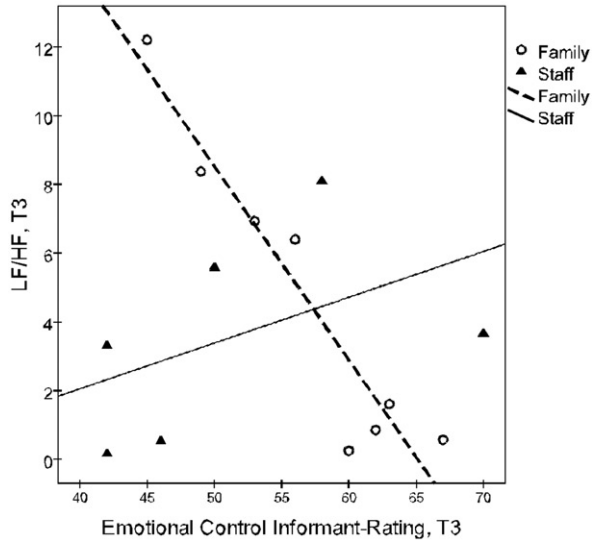

Figure 3. A scatterplot of *T*-scores of informant ratings (family and staff) of participant's emotional control and LF/HF index at Time 3 (T3). Higher scores reflect poorer emotional control (family: $R^2 = 0.96$, $p < 0.001$; staff: $R^2 = 0.23$, $p = 0.332$). The difference in the correlations obtained by the two groups—family vs staff—is significant ($p < 0.001$).

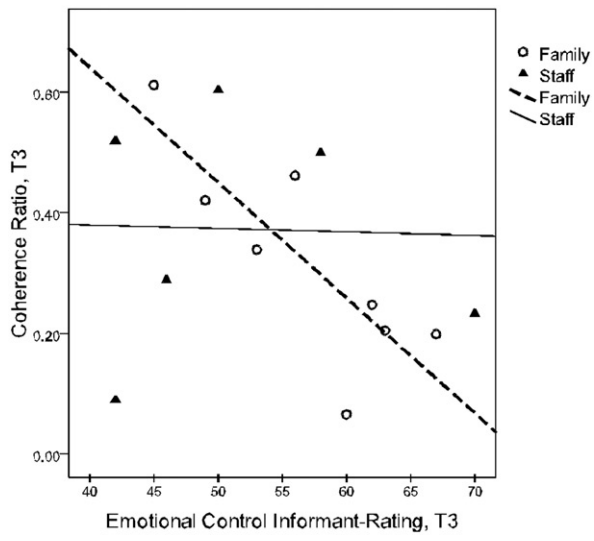

Figure 4. A scatterplot of informant ratings (family and staff) of participants' emotional control and coherence ratio at Time 3 (T3) (family: $R^2 = 0.82$, $p = 0.005$; staff: $R^2 = 0.001$, $p = 0.953$). The difference in the correlations obtained by the two groups—family vs staff—is significant ($p = 0.055$).

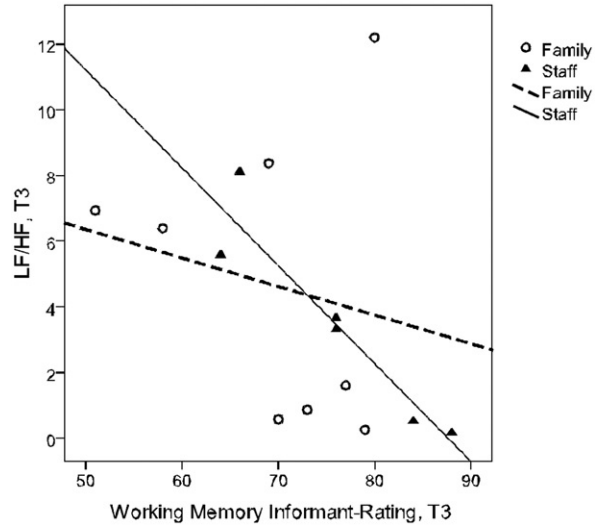

Figure 5. A scatterplot of informant ratings (family and staff) of participants' working memory and the LF/HF index at Time 3 (T3) (family: $R^2 = 0.004$, $p = 0.891$; staff: $R^2 = 0.88$, $p = 0.005$). The difference in the correlation coefficients obtained by the two groups—family vs staff—is significant ($p = 0.031$).

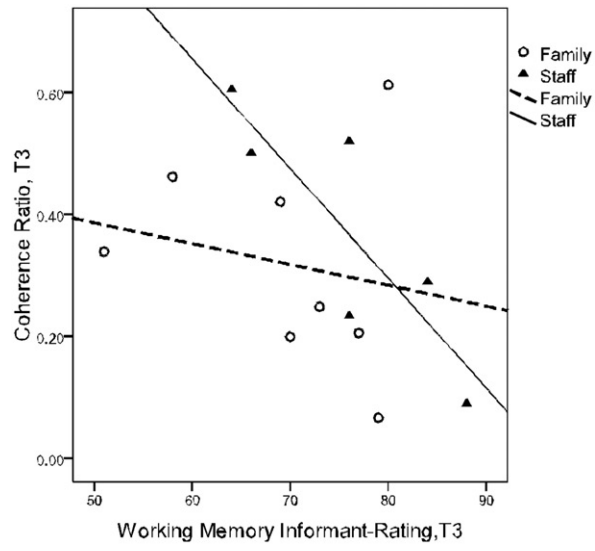

Figure 6. A scatterplot of informant ratings (family and staff) of participants' working memory and coherence ratio at Time 3 (T3) (family: $R^2 < 0.001$, $p = 0.97$; staff: $R^2 = 0.74$, $p = 0.028$). The difference in the correlation coefficients obtained by the two groups—family vs staff—is not significant ($p = 0.150$).

$p = 0.005$. At Time 2 (pre-treatment) a 1-point decrease in Category Test errors increases LF/HF (from Time 2 to Time 3) by 0.18 ($p = 0.005$). Descriptive statistics of the neuropsychological measures are presented in Table III.

HRV and continuous performance test (IVA + Plus CPT). Improvement in HRV was assessed by comparing indices computed for data collected during the first 5 minutes of recording vs the last 5 minutes of a 10-minute session. At Time 3, there was a significant association between IVA + Plus CPT Attention Quotient and the participant's LF/HF index in the last 5 minutes of recording, $r = 0.77$, $p = 0.009$. Participants who increased in LF/HF values during the last 5 minutes of the recording had higher IVA + Plus CPT Attention Quotient scores. A scatterplot in Figure 8 indicates

that the two variables are linearly related such that as LF/HF increases so does the Attention Quotient.

Judgement of self-monitoring: BRIEF informant report (family) and self-report

One sub-scale of the BRIEF-A is designed to rate the individuals' ability to self-monitor while working on a task (the participants' self-appraisal of how well they measure their ability to complete a task). The correlation between the participants' self-rating of how well they were able to self-monitor while working on a task *and* scores reported by staff at post-treatment was not significant (perhaps because of the small sample [$n = 6$] and an outlier). With respect to the families' rating of the participants' behaviour, no statistically meaningful relationship was observed between the families' rating of the participant and the participants' self-rating on this particular ability at pre-treatment (Time 2), $r(5) = 0.55$, $p = 0.202$. However, at post-treatment testing, not only was there a significant, strong relation between family rating and participant rating, $r(5) = 0.84$, $p = 0.018$, but how the participants rated themselves at post-treatment testing also correlated with how the families rated the participants at pre-treatment testing, with a strong linear relationship, $r(5) = 0.86$, $p = 0.013$ (see Figures 9–10). This result indicates that, at post-treatment, the participants' self-rating became more closely aligned to how others (family members in particular) perceived their behaviour. It is noteworthy that following the intervention the participants reported their functional ability in a way that was consistent with the assessment of others who observed them.

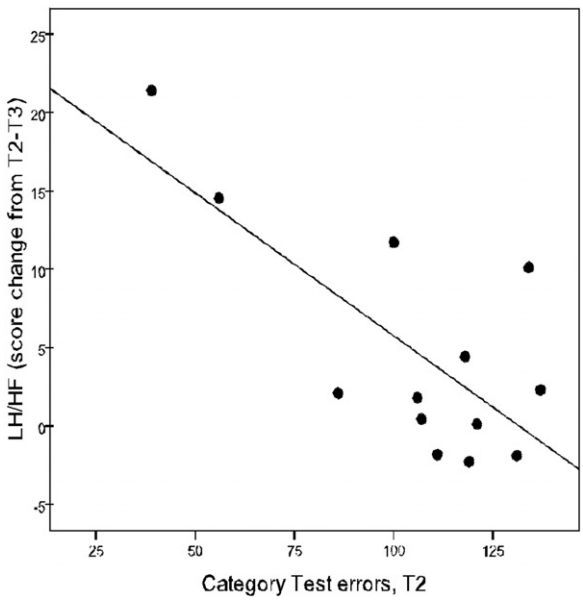

Figure 7. A scatterplot of Category Test errors (Time 2) and an index of improvements in LF/HF from pre-treatment (Time 2) to post-treatment (Time 3), $R^2 = 0.53$, $p = 0.005$.

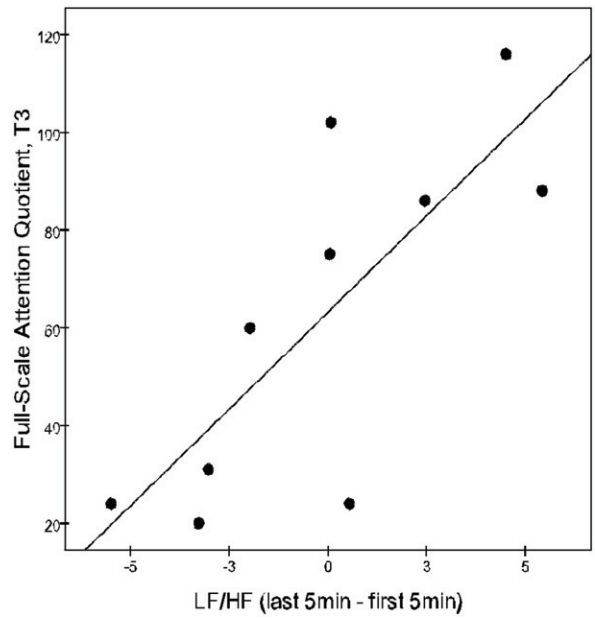

Figure 8. A scatterplot of Full Scale Attention Quotient (FAQ) at Time 3 and an index of LF/HF change—the first 5 minutes of recording vs the last 5 minutes taken at Time 3 ($R^2 = 0.60$, $p = 0.009$).

Table III. Medians and interquartile ranges (*IQR*) of neuropsychological tests: IVA + Plus CPT and Category Test.

	Time 1		Time 2		Time 3		
	Mdn	*IQR*	Mdn	*IQR*	Mdn	*IQR*	*p*-values
IVA + Plus CPT[a] Full Scale Attention Quotient	57.5	72.25	64	55	67.5	67.5	Time 1 to 2 = 0.018[b] Time 2 to 3 = 0.894
Category Test errors	116	29	111	33	109	40	Time 1 to 2 = 0.157 Time 2 to 3 = 0.624

[a]IVA + Plus CPT is a version of the continuous performance test that combines visual and auditory stimuli. [b]Performance change from Time 1 to Time 2 is significant, but the change in absolute score is not a meaningful *clinical* change [55]. Both Time 1 and Time 2 scores are in the severely impaired range.

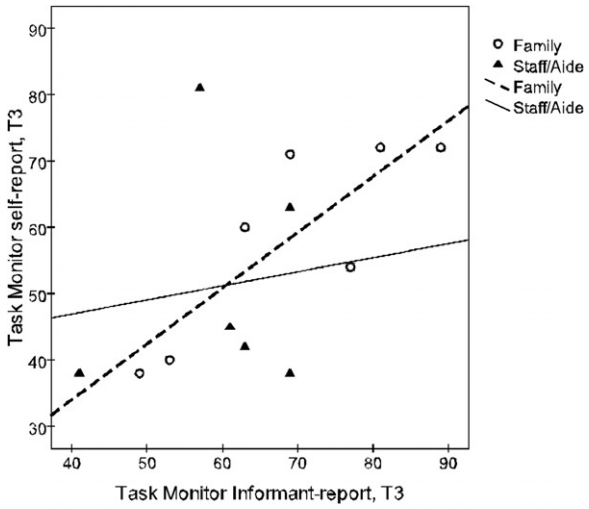

Figure 9. A scatterplot of task monitor scale of the BRIEF self-report and informant report at Time 3, post-treatment (family: $R^2 = 0.70$, $p = 0.018$; staff: $R^2 = 0.02$, $p = 0.81$). The difference in the correlations obtained by the two groups—family vs staff—is not significant ($p = 0.066$).

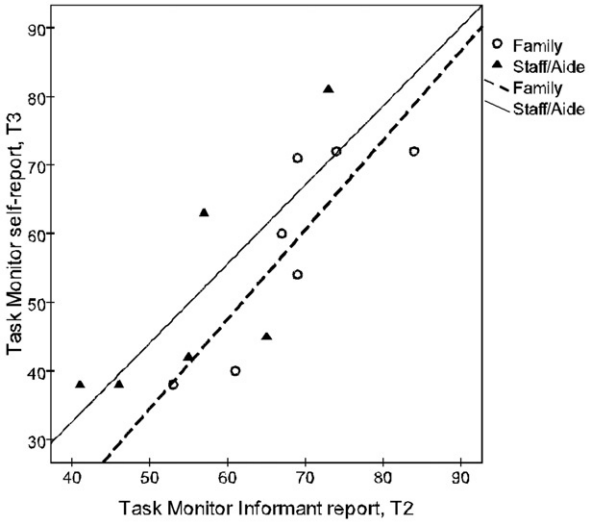

Figure 10. A scatterplot of task monitor scale of the BRIEF self-report at post-treatment, Time 3 and informant report at pre-treatment, Time 2 (family: $R^2 = 0.74$, $p = 0.013$; staff: $R^2 = 0.62$, $p = 0.065$). The difference in the correlations obtained by the two groups—family vs staff—is not significant ($p = 0.993$).

Discussion

This study provides the first empirical demonstration that self-regulation training using psychophysiological methods based on HRV biofeedback can be used to enhance coherence in individuals with moderate-to-severe chronic brain injury. No other similar studies have been found in the literature. The findings help to elucidate the relation between psychophysiology and neuropsychology in individuals with chronic brain injury. Studies have shown that the characteristic of the HRV pattern called 'resonance' (reflected in the coherence measures reported in the current study) is connected to self-regulation of emotions, behaviour and thinking [25, 26, 29]. This pilot study indicated an association between HRV and cognition and behaviour, although a causal relationship was not demonstrated. At Time 3, there was a significant association between IVA+Plus CPT Attention Quotient and the participants' ability to increase resonance from the first 5-minute epoch to the second 5-minute epoch during their 10-minute HRV recording session. In addition, pre-treatment Category Test scores predicted which individuals would benefit most from HRV biofeedback and which individuals would register the greatest increases in HRV indices. Participants with the fewest errors in the Category Test at pre-treatment attained the highest scores in HRV at Time 3. This result indicates that those who are cognitively more intact achieved the highest levels of resonance (coherence) after treatment.

Furthermore, this study revealed that, despite significant improvements in the measurements of the individual's physiological behaviours, no significant improvement occurred in executive functions, as measured by neuropsychological tests and rating scales. This null finding may be due to the fact that the participants in this study were cognitively impaired to a severe degree. Accordingly, greater cognitive ability may be needed to demonstrate any significant improvement on the chosen outcome measures. This possibility is supported by the findings of Duncan et al. [12] and the premise of Bertisch et al. [70] that requisite skills need to be in place for individuals to benefit from treatment. It would be important, therefore, for future work to focus on individuals with a higher cognitive level.

Confirmation of these results in larger studies would provide support for using HRV biofeedback training in assessing cognitive functions, both attention and problem solving, as measured by standard neuropsychological tests. HRV has the potential to serve as an indirect but objective measure of brain function in cases where neuropsychological tests prove problematic, such as when patients have motor or sensory impairments. Currently, changes in the behaviour of an individual with brain injury (specifically involving frontal lobe damage) as reported by the individuals and their relatives are significant, but such changes can be difficult to quantify. Standard neuropsychological test scores typically show little relation to the behaviours that individuals with neurological deficits manifest in their daily routines [13, 71–73]. Future work should address how HRV measures compare to standard neuropsychological tests in psychometric properties

(e.g. convergent and discriminative validity, reliability, etc.).

This study indicates that individuals with severe and chronic brain injury can demonstrate improvements in HRV biofeedback after a relatively short treatment period. Two different indices of HRV were used to quantify treatment gains: LF/HF [30] and a measure based on HeartMath's coherence ratio [50]. The participants learned how to operate a portable biofeedback instrument in order to pursue their biofeedback training goals at home. This study found a significant correlation between HRV and BRIEF informant scores at Time 3 (post-treatment). The results provide evidence that an association does exist between an individuals' HRV performance and their emotional control, even in cases of severe neurological damage. Although the hypothesis of the study—that increases in behavioural and cognitive control would be related to increases in HRV resonance—was not supported, participants who were rated by their informants as *in control* of their emotions and their cognition achieved the highest scores in HRV resonance. The behavioural ratings from family and staff at baseline *predicted* which individuals would make the greatest gains in HRV training. Notably, however, this was a short-term study. It is possible that the short-term follow-up immediately after biofeedback training prevented one from observing long-term effects on behaviour. It is possible that a causal association between HRV resonance and behavioural or cognitive control might have emerged over a longer time period, given the evidence for improved emotional and psychological control with increased HRV resonance [24, 46, 74, 75].

The correlation between the participants' self-ratings of how well they were able to self-monitor while working on a task and the staff ratings of the participants in this area was not significant. However, it has been noted that informant observations depend on the informants' relationships with the individuals [68, 69]. Especially where the family is concerned, conflicting views of an injured individual's identity, cognition and behaviour create tension both in and beyond the injured individual. Not only must the family adjust to radical changes in the individual's functional abilities (such as poor memory, which may cause loss of employment), the family must also cope with the discrepancy between how the family appraises the injured individual and how the injured individual appraises him or herself [68, 76]. At pre-treatment (Time 2), a moderate sized, but not statistically significant relationship was observed between family ratings of the participant and the participants' self-ratings on their ability to 'self-monitor.' At post-treatment testing, however, a significant relation emerged, with a large correlation coefficient between family ratings and participant ratings; in addition, the participants' self-ratings at post-treatment testing correlated strongly with the families' ratings at pre-treatment testing. These findings indicate that, at post-treatment, the participants' self-ratings became more closely aligned to their family's perceptions of their behaviour (see Figures 9 and 10).

This study had several limitations. Because this was a short-term study, the duration of treatment was relatively short for this population. More extended treatment may yield more functional changes in individuals. More functional changes may also result from efforts to incorporate HRV biofeedback training more fully into the participants' life, such as by scheduling in-home training sessions and training both staff and family to encourage more practice by the participants. Nonetheless, it should be noted that this was a novel attempt to determine if biofeedback training was possible with this type of population, and that the successful demonstration that such training was possible could have heuristic value for future, more intensive work in this area.

Another limitation of this study is that the sample size was small and the experiment was a prospective cohort pilot study. Due to the small sample size, no statistical corrections were performed to adjust for the probability of Type I errors. Thus, the conclusions drawn here are preliminary. Future work on HRV biofeedback for individuals with brain injury should rely upon a larger sample, using a randomized clinical trial to test the functional effects of HRV treatments. Research also could test if certain levels of HRV resonance measures are useful as *indicators* of intact cognitive abilities and by using receiver-operating-characteristic (ROC) curve analysis, ascertain cut-off points for intact as opposed to impaired cognition (specifically deficits most related to attention and problem-solving). Future studies should further evaluate whether HRV biofeedback training helps to improve the participants' insight into their own behaviour and the extent to which any insight leads to better relations with their family members.

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