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The Effectiveness of Neurofeedback and Heart Rate Variability Biofeedback for Individuals with Long-Term Post-Concussive Symptoms

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Abstract

Case studies have shown that low resolution electromagnetic tomography (LoRETA) neurofeedback is effective for many psychological disorders, but it's effectiveness for individuals experiencing persistent post-concussive symptoms (PPCS) is uncertain. Individuals with PPCS (n = 7) received an eight-week LoRETA neurofeedback and heart rate variability biofeedback intervention. Change in symptoms, driving simulation performance, electroencephalographic z-score deviations, and heart rate variability were compared to PPCS (n = 9) and healthy (n = 8) control groups. Statistical analyses revealed that the intervention significantly reduced electroencephalographic z-score deviations ($p < 0.005$) compared to PPCS controls. Additionally, headache, nausea, and dizziness symptoms were reduced in the intervention group ($p = 0.003$) and the PPCS controls ($p = 0.001$) compared to healthy controls. Participants responded variably to the intervention, therefore case analyses were considered and revealed that some individuals responded to the intervention while others did not. Future studies with larger populations and longer follow-up times may help evaluate whether there are commonalities between positive responders.

Keywords

Concussion, persistent post-concussive symptoms, neurofeedback, LoRETA neurofeedback, heart rate variability biofeedback, biofeedback

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Table of Contents

List of Figures

List of Appendices

1 Introduction

1.1 Concussion and Persistent Post-Concussion Symptoms

A concussion (often used interchangeably with mild traumatic brain injury) is defined as a traumatic brain injury that is induced by biomechanical forces, which results in an array of signs and symptoms that can include somatic, cognitive, behavioral, or emotional changes, sleep disturbances and or balance problems. Most concussions resolve spontaneously, but some studies indicate that as many as 43% of individuals continue to experience persistent and disabling problems months beyond their injury (1). Persistent post-concussive symptoms (PPCS) refer to the lack of clinical recovery in 10-14 days for adults, and four weeks for children (2). Persisting symptoms can lead to a condition known as post-concussion syndrome (PCS; 2).

PPCS are problematic because they decrease quality of life by several means, such as reduced social interactions, difficulty continuing previously enjoyed past-times or resuming pre-injury physical capabilities and employment tasks (3). This is likely a factor that contributes to approximately 42% of individuals not returning to work in six months following a concussion (4). Further, 28% of those who do return to work following a concussion do not return to the same level of work as before their injury (4); many individuals require modified return to work duties. Returning to work while continuing to suffer PPCS increases the risk of subsequent concussions (Mansfield et al. 2015) and unintentional injury, such as falls and motor vehicle accidents (5).

Recent literature has identified that PPCS are associated with various physiological impairments, including reduced cerebral vasoreactivity as the severity of PPCS increases (6), and reduced functional connectivity compared to healthy individuals (7). Increases in PPCS also correlate with reductions in white matter integrity, indicating delayed processing speed (8). These physiological deficiencies can manifest in numerous ways, such as reduced attention and focus, increased reaction time, and disruptions in vision; all factors necessary for the safe operation of a motor vehicle (9)

1.2 Concussion, PPCS and Driving

Driving requires planning, anticipation, foresight, concentration, inhibition of certain stimuli, problem-solving, the ability to simultaneously process large amounts of stimuli, and quick reactions, all of which can be impaired by a brain injury (10). It has been suggested that individuals who experience a concussion should not drive for 24 hours (11). But, driving restrictions for individuals with PPCS depends on medical professional's discretion, which is influenced by type and severity of symptoms (11). Usually driving capacity is initially evaluated by a medical professional, but only 49% of physicians 'almost always' provide driving guidance following a concussion (12). A lack of driving guidance is concerning because failing to do so may result in returning to driving prematurely. This is illustrated through findings such as 66% of collegiate athletes continue to drive following a concussion (13). Furthermore, I am not aware of any research-based recommendations regarding driving with PPCS.

In a subjective questionnaire, more than half of the participants continuing to experience PPCS 15 months (on average) post-injury indicated that they were experiencing difficulties with fatigue, concentration, memory, anger and anxiety that impacted their overall daily activities (14). This study identified that these participants developed coping mechanisms to compensate for their difficulties while driving, including avoiding rush hour traffic, breaking up drives and minimizing lane changes. Although these adaptations may allow these participants to drive, not everyone experiencing PPCS is able to make these adaptations. For that reason, identifying and trying to fix the source of the problem would be much more beneficial.

Making matters even more complex, resolution of concussive symptoms does not necessarily indicate a return to pre-concussion functioning. Individuals who suffered a concussion but are asymptomatic exhibit reduced driving capabilities, as assessed in a driving simulator (15). Their deficiencies included more frequently crossing over the road's edge and weaving within their lane when navigating curves. Recently concussed individuals (two weeks to three months post-concussion) also exhibit increased reaction time during simulated driving performance (16), and delayed traffic hazard perception (17). Additionally, compared to the general population, accident rates are more than

double for persons six to nine years following traumatic brain injury (18). The combination of physiological deficits in those experiencing PPCS, as well as reduced driving performance in people after a concussion or traumatic brain injury, emphasize the need to evaluate driving performance in individuals with PPCS.

1.2.1 Simulated Driving

Driving simulators are a valuable alternative to on-road driving assessments because they provide a safe environment and allow scripted events to happen for each participant (19). They have successfully been used to evaluate the driving habits of various populations, including older adults (20), individuals with glaucoma (21), and people with multiple sclerosis (22). Driving simulation has also proven effective for providing driving education to adolescent drivers (23, 24). Driving simulation can offer a valid and reliable assessment of driving performance (19), and reflects real-life driving (25). Furthermore, simulator-based assessments can also be more sensitive than an external rater to long-term driving performance in individuals with a traumatic brain injury (26).

Limited previous literature has evaluated the effects of concussion and PPCS on driving, therefore it is difficult to know what variables should be evaluated. Some of the observed variables have included reaction time from the moment a programmed stimulus appeared to the time of an evasive maneuver (e.g. pressing the brake or evasive steering; 16), as well as number of traffic law violations, crashes, lane excursions, lane position and speed (15).

1.3 Concussion, PPCS and Mental Health

Concussions are often associated with anxiety, depression, mood changes, and poor global health (27). These difficulties can continue for individuals with PPCS, but it is unclear whether PPCS is the cause or merely an association. Some evidence suggests that psychological factors such as legal involvement and premorbid psychological illnesses contribute to the development and continuation of PPCS (28). Additionally, a lower level of psychological resilience, increased trait anxiety and embitterment can affect the emergence and continuation of PPCS (29).

PPCS also impacts aspects of life satisfaction. For example, individuals with PPCS report a low self-assessed quality of life (30). Reported difficulty initiating and staying asleep (31), as well as migraine and tension-type headaches (12), also contribute to life dissatisfaction. Following a concussion, depression is associated with greater psychosocial dysfunction, more psychological distress, and more neurobehavioral dysfunction (27). This results in a negative cycle, where difficulty continuing normal activities results in a reduction of those activities, which increases psychosocial dysfunction and psychological distress, and the cycle continues.

Mood disruptions resulting from (or in combination with) PPCS can influence fundamental components of driving. Individuals with major depressive disorders perform worse on working memory tasks (32), have slowed reaction time, and are susceptible to fatigue (33). Additionally, increased anxiety can draw focus to threat-related stimuli, which reduces concentration and information processing (34). Increases in impulsivity, irritability and aggression (35) can also result in dangerous and at-risk driving behaviours.

1.4 Generalized Anxiety Disorder Scale

Anxiety is one of the most common PPCS (35). The 7-item Generalized Anxiety Scale (GAD-7) detects generalized anxiety, and can also detect post-traumatic stress disorder, panic disorder and social anxiety disorder (36). It is a reliable and valid measure of anxiety in the general population (37), the elderly (38) and in primary care (39). It is preferred for individuals with PPCS because they often experience vision difficulties and headaches with prolonged reading and concentration, and this questionnaire is very short.

1.5 Rivermead Post-Concussion Symptoms Questionnaire

Questionnaires have been created to evaluate some of the most common concussion symptoms. The Rivermead Post-Concussion Symptoms Questionnaire (RPQ) is a 16-item questionnaire that evaluates the severity of symptoms such as headache, dizziness, nausea, poor concentration, forgetfulness, etc. It demonstrates good test-retest and inter-rater reliability (40). Furthermore, when evaluating headaches, dizziness and nausea

separately from the remaining 13 items, it has a good test-retest reliability and validity at three months post injury (41). It is also very short, and therefore is easy for individuals with PPCS to complete.

1.6 Treatment of Concussion and PPCS

Since the return protocol for acute concussions is well-established (2), it can easily be adhered to and implemented by medical professionals. When an individual suffers a concussion, they often are instructed to follow a graded return to work/learn/play protocol. They begin with a 24-48 hour cognitive and physical rest period. Afterwards, they continue gradually returning to everyday activities, while reducing this activity if symptoms increase (2). This protocol facilitates proper immediate treatment, and may help increase the likelihood of resolution.

PPCS, however, is much more difficult to treat because the best practices for rehabilitation programs have not yet been universally adopted. Individualized treatment plans that target medical, physical and psychosocial symptoms are recommended (2). Accordingly, specialists like physiotherapists, occupational therapists, speech and language specialists, optometrists, or massage therapists may be consulted. Patients may also seek psychological treatment to aide common symptoms like depression, anxiety, or mood changes (42).

Although these specialists may reduce or eliminate symptoms, this is not always the case. For instance, treating the manifested symptoms does not necessarily address the cause; the root of the symptom may be due to altered physiology. This is starting to be researched more. For example, exercise used to be discouraged for individuals experiencing symptoms following a concussion (43). But, we now know how beneficial sub-symptom aerobic exercise following a concussion can be (44). Treating the manifested symptom may be beneficial and allow individuals with PPCS to live with their injury, but research needs to be done to investigate how to identify the physiological damage and how to rectify it.

1.7 Heart Rate Variability

Biomechanical forces that result in concussions affect other organs within the body, not just the brain (Cernak and Noble-Haeusslein, 2009). Furthermore, if an organ and the organ's control center (the brain) are injured, it can result in additional difficulties. For example, the autonomic nervous assists in controlling the heart, including whether the heart should increase or decrease its strength and rate of heart beats (45). The specific regions of the brain that are involved in regulation of the autonomic nervous system are still debated, but it has been determined that it includes contribution from areas such as the amygdala and prefrontal cortex (46). This information indicates that there is a brain-heart connection, and a disruption to this connection (e.g. following a concussion) can result in a cascade of symptoms that can include arrhythmias, ischemia, myocardial infarction, and altered sympathetic or parasympathetic activation (Leddy et al., 2007).

Heart rate variability (HRV) is the natural beat-to-beat variability in heart rate. It is representative of autonomic function and sympathetic-parasympathetic balance (47). It can be measured in both time- and frequency-domains, including measures such as the square root of the mean squared differences of consecutive normal intervals (RMSSD), and standard deviation of the normal interval (SDNN). SDNN is a good global measure of variability and it reflects cardiovascular adaptability to individual and environmental changes (48). Frequency-domain measures include power in various bands (49).

Healthy people normally exhibit a beat-to-beat variation in their heart rate, but HRV is decreased when the autonomic nervous system is impaired (50). Decreased HRV is associated with reduced social and emotional functioning, including social cognition, empathy and alexithymia (48). HRV is altered in those suffering a concussion, including low amplitude and reduced rhythmicity (Thompson and Hagedorn, 2012). Further, some individuals suffering PPCS have reduced parasympathetic activity and hyperactive sympathetic activity and heart rates (51). This is problematic because it results in a heightened and prolonged state of flight or flight, which may contribute to feelings of nausea, dizziness, and inability to sleep – all of which are common PPCS (2).

HRV biofeedback intends to repair sympathetic-parasympathetic balance, as well as baroreflex activity (Lehrer et al., 2003). Using an electrocardiograph (ECG), it provides beat-to-beat data to a participant while they maintain a slow, set breathing rate. This set breathing rate maximizes respiratory sinus arrhythmia, which increases the heart rate when inhaling, and decreases the heart rate when exhaling (52). Respiratory sinus arrhythmia works in combination with the information that baroreceptors are detecting regarding blood pressure to increase the variability of HRV (53). More variability (increased HRV) reflects increased reflex efficiency, which is a result of more controlled autonomic activity (54). It also translates to larger oscillations in heart rate, which promotes increased parasympathetic control and reduced sympathetic control (55).

A recent review on HRV biofeedback research shows that it may positively affect illnesses such as asthma, COPD, irritable bowel syndrome, cyclic vomiting, recurrent abdominal pain, fibromyalgia, cardiac rehabilitation, hypertension, chronic muscle pain, pregnancy induced hypertension, depression, anxiety, post-traumatic stress disorder, and insomnia (56). HRV biofeedback improves cognitive functioning and emotional regulation in some individuals experiencing a brain injury (48). It may also contribute to improved attention (57), enhanced executive functioning (58) and superior problem-solving abilities (59). Research is limited on HRV biofeedback's effects on PPCS, but it has been indicated that it may be effective with this patient group in reducing symptoms (including headache) and increasing mood (60, 61).

1.8 Neurofeedback

Electroencephalograph (EEG) biofeedback (neurofeedback), has been used for decades to improve rehabilitation and brain function. It has been used to improve attention, impulse control (62), agreeableness and feelings of confidence and composure (63), and reduce stress (64). It also helps reduce the symptoms of illnesses such as attention deficit hyperactive disorder (65), post-traumatic stress disorder (66), depression (67), and epilepsy (68). Neurofeedback has evolved from measuring brain surface area activity, to source localization of neural activity. This form of neurofeedback is known as low-resolution electromagnetic tomography (LoRETA) neurofeedback (69). It uses information from the electrical leads placed on the scalp to derive a 3D representation of

the activation of various regions of the brain– not just where it has manifested on the superficial area of the brain/scalp. LoRETA neurofeedback allows the user to see, in real time, the amplitude of electrical activity at specific brain regions, and they can therefore self-regulate this electrical activity (69).

Benefits to LoRETA neurofeedback include that it is a non-invasive procedure, and that it shows functional activity in specific brain regions. LoRETA neurofeedback also enables individualized rehabilitation, which is one of the biggest limitations of traditional brain injury interventions (70). Based on operant-conditioning principles, users receive feedback on their brain activity, which is expressed as z-scores relative to a normative population (healthy age-matched population). This activation is associated with some form of audible or visual cue (e.g. music playing or a light turning on), when brain activity is within the set range compared to the healthy population (i.e. correct). Over time, users learn to exhibit correct brain activity. With more LoRETA neurofeedback experience, this trained activity can become more habitual, therefore leading to routine improvements (71).

LoRETA neurofeedback commonly uses Brodmann areas to classify areas of deviant brain activity (72-74). Each area is associated with different cognitive functions; inappropriate brain activity (hyperactive or hypoactive) in different areas can be associated with specific PPCS (71). Since every PPCS case is unique, it requires an individualized LoRETA neurofeedback treatment protocol. This makes it difficult to perform standardized studies, because a blanket treatment will not necessarily work when each person demonstrates inappropriate brain activity in different areas of the brain.

The majority of research regarding LoRETA neurofeedback treatment for various ailments is based on case studies. For example, LoRETA neurofeedback improved memory, attention, and global cognitive scores in eight participants with cognitive dysfunction and dementia (75). Additionally, LoRETA neurofeedback has provided cognitive enhancement in individuals with a traumatic brain injury (72). LoRETA neurofeedback has also proven beneficial for PPCS in small case studies (76). Accordingly, LoRETA neurofeedback seems to be effective for several clinical

conditions, but systematic studies with larger sample sizes needs to be completed in order to evaluate the effectiveness of LoRETA neurofeedback for individuals with PPCS.

LoRETA neurofeedback is often used as a treatment modality in conjunction with HRV. This is because the neuroanatomical networks and structures that affect and control HRV can be influenced by neurofeedback; therefore, changes in HRV can cause changes in these neuroanatomical networks and structures (77). Combining these modalities can be effective when treating individuals with anxiety and depression (78), as well as individuals with traumatic brain injury (79).

2 Purpose and Hypothesis

2.1 Purpose

The purpose of this thesis was to determine whether HRV biofeedback in combination with LoRETA neurofeedback could reduce symptoms and/or improve simulated driving performance in individuals suffering from PPCS.

2.2 Hypothesis

1. Individuals with PPCS that receive HRV biofeedback and LoRETA neurofeedback will have reduced symptoms after an eight-week intervention, compared to a group with PPCS that does not receive HRV biofeedback and LoRETA neurofeedback.

2. Brain activity in specific areas will be normalized in individuals with PPCS who receive LoRETA neurofeedback and HRV biofeedback, compared to people with PPCS who do not receive the intervention, and also to a healthy control group.

3. Individuals undergoing an intervention involving HRV biofeedback and LoRETA neurofeedback will exhibit greater performance improvements in the driving simulation task compared to individuals with PPCS who do not receive the intervention, and compared to a healthy control group.

3 Methods

3.1 Participants

Thirty-one individuals were recruited to participate in this study; which was approved by Western University Health Science Research Ethics Board (Appendix A). Participants with PPCS had to be 18 years of age or older, have previously suffered a clinically diagnosed concussion, completed the BrainEx 90 concussion rehabilitation program, and still experiencing ongoing symptoms. They also had to be fluent in English, hold a valid driver's license, and be capable of using hand-held devices. Healthy participants also had to be 18 years of age or older, have not suffered a concussion in the last two years, be fluent in English, and hold a valid driver's license.

Participants were withdrawn from the study if they were unable to complete the entire baseline assessment. This resulted in the loss of seven participants that experienced a worsening of symptoms and could not complete the driving simulator task. Therefore, 16 participants with PPCS were randomized into the intervention and control groups, and eight healthy individuals were part of the healthy control group. This resulted in seven participants in the intervention group (48.6 ± 13 years old, four females), nine participants in the PPCS control group (54.6 ± 7.6 years old, six females), and eight healthy control participants (50.1 ± 15.5 years old, four females).

Information about the participants' PPCS were collected during the baseline assessment. All PPCS individuals (intervention and control participants) reported that they continued to experience headaches, along with a variety of other symptoms. Six (of seven) intervention participants reported experiencing emotional changes (anxiety, anger, inability to regulate emotions), and four (of seven) reported experiencing balance problems. Additionally, three (of seven) intervention participants reported experiencing dizziness, light sensitivity, memory problems, difficulty focusing, and feelings of overstimulation. Eight (of nine) PPCS controls reported experiencing noise sensitivity, six reported experiencing light sensitivity, and five reported experiencing emotional changes (anxiety, anger, inability to regulate emotions) and balance problems.

3.2 Intervention Protocol

3.2.1 Baseline and Follow-Up Assessment

Participants were initially contacted via email about interest in the study; their response prompted an informational email. They then met with a study investigator at the iMobile Research Lab at Western University, where together they reviewed the letter of information. Once all questions were answered and they signed the consent form, the baseline assessment began.

The participant was first measured and fitted with a 19-lead EEG cap (Electro Cap International, Eaton, Ohio). Each electrode placement corresponded to specific locations on the scalp according to the 10-20 International System for electrode placement (80). The leads were then filled with a water-soluble conducting gel (Electro-Gel, Electro Cap International, Eaton, Ohio). An abrasive gel (NuPrep) was used as skin preparation for the attachment of an electrode to each earlobe. Additionally, one electrode was also taped to the participants chest, below the left clavicle, for ECG monitoring.

The participant then completed three individual brain function assessments. First, they sat still and silent for five-minutes for eyes open EEG recordings. As sensitivity to light and screens can be problematic for individuals suffering PPCS, they were instructed to look at a spot on the wall. Afterwards, they had a three-minute resting EEG measurement taken with their eyes-closed. Finally, they performed a 10-minute reaction time test, where they pressed a button on a handheld toggle when a large blue circle appeared. Before they completed the actual reaction time test, they had to pass a pre-test that had the same rules, but provided immediate feedback about whether the responses were correct/incorrect in pressing/not pressing the button. All of this was completed with the study investigator in the neighboring room so as to not distract or stress the participant. There was a one-way window for the study investigator to observe the participant, and the participant was informed that they could either wave or call on the investigator if they had any questions or issues.

Brain function assessment was followed by a break. Afterwards, the participant completed the RPQ and GAD questionnaires (Appendices B and C), and then proceeded

to the driving simulation task. This was performed on a CDS-200 DriveSafety™ simulator, which includes a steering wheel and dash display from a Ford Focus, a gas and brake pedal, and three computer screens for viewing. The simulator was adjusted for the participants comfort, ensuring that they were the appropriate distance from the screens, and they were comfortable with the height and tilt of the steering wheel and distance to the pedals.

The simulation drive began with three acclimation drives, which are part of an evidence-based simulator sickness mitigation protocol in the iMobile laboratory (24). The acclimation drives included driving straight down the road at 50 km/hour with no other vehicles on the road, driving around a city block involving four consecutive left-hand turns while navigating traffic, and lastly driving around a city block involving four consecutive right-hand turns while navigating traffic. Between each acclimation drive, participants were screened for symptoms of simulator sickness using a modified version of the motion sickness assessment questionnaire (81). Participants rated feelings of sweatiness, dizziness, and potential to vomit on a scale of 1 (not at all) to 10 (severely). Participants also had the option to take breaks between drives as needed.

Finally, participants performed one of two simulator drives. Participants were informed that the drive was supposed to simulate driving in the real world, so they were informed that other drivers may not obey traffic laws as expected. The two simulator drives contained identical elements, but in different orders. Both drives ended at a highway on-ramp, and they were instructed to either go towards London or Toronto, depending on which simulation drive they were completing. The drive was approximately 10 minutes in length, and included five scripted events: an unexpected pedestrian crossing the street in front of the car; a car making a rapid lane change in front of the driver; a sudden change in traffic lights from green to yellow (go-no-go); a way-finding task (appropriately picking the ramp to London or Toronto based on earlier instruction); and a car suddenly pulling out of a driveway in front of the participant. As we are interested in measures of driving performance that are directly related to safety, we evaluated the participant's responses related to two of the scripted events that involve responding to critical roadway information: the unexpected pedestrian crossing the street in front of the

car and a car suddenly pulling out of a driveway in front of the car. In specific, we quantified the participants' reaction times between the onset of the scripted event (e.g. first appearance of the pedestrian) until the participant responded by steering or braking. We also evaluated whether the participants were in a collision during their driving simulator task. Involvement in a collision ended the driving simulation, which may have prevented the participant from completing the pedestrian crossing or car pull-out scripted event. The mean lane deviation for the duration of the driving simulation task was also evaluated, using the average deviation from the center of the lane.

After eight weeks, all participants returned to complete another brain function assessment, RPQ and GAD, and driving simulator acclimation and drive. The final simulator drive was the alternate drive they had not completed in their baseline assessment. For example, if they completed Drive 1 in their baseline test, then they would complete Drive 2 in their follow-up assessment.

3.2.2 LoRETA Neurofeedback and HRV Biofeedback Intervention

Participants in the intervention group received an Android tablet (either a Craig 7" 1GB 6.0 "Marshmallow" Tablet, New York, New York or a Samsung Galaxy Tab A 7' 8GB Android 5.1 "Lillipop" Tablet, Seoul, South Korea) and heart rate variability training tool (Evoke Waveband, Evoke Neurosciences, New York, New York) upon completion of their initial assessment. They were shown how to use the equipment, and instructed that they should perform a HRV biofeedback session every morning and night for eight weeks. Each HRV biofeedback session involved placing the Waveband just below their elbow, opening the application on their tablet (Mindja, Evoke Neurosciences, New York, New York), and doing a 5-minute exercise in which they were cued to breathe at their resonant frequency (approximately six breaths per minute; 82). Points were awarded as their HRV improved. Participants were also provided with a log book to record the dates and times of their completed sessions.

LoRETA neurofeedback is based on measuring EEG signals, comparing them to age-matched population norms, and providing feedback to normalize deviant signals. We performed these measurements using a 19-lead EEG cap (Evoke Neurosciences, New York, New York). Assessments were completed at the iMobile research laboratory at Western University, London, Ontario, and interventions were completed in a private room at Parkwood Institute, London, Ontario. Each participant in the intervention group was scheduled to participate in three sessions per week (usually Mondays, Wednesdays, and Fridays), for 8 consecutive weeks. This totaled an expected 24 LoRETA neurofeedback sessions and 112 HRV biofeedback sessions (24 of which to be completed with the study investigator during the regularly scheduled neurofeedback training sessions). Typically, their sessions were at the same time of day.

Based on their initial assessment, an individualized LoRETA protocol was developed for each participant. This involved identifying the Brodmann areas of the brain and the EEG frequencies that were most deviant from age-based normal values, and targeting them for biofeedback. The set of Brodmann areas and frequencies were constant for each of the participants throughout the study. Each LoRETA neurofeedback session was broken up into 10 exposures of two-minute duration, for a total of 20 minutes of training. Participants were instructed to “relax, focus, and turn on the green light”, which would appear on a computer screen in front of them. The light turned green when the participants were appropriately activating the target cerebral areas at the appropriate amplitude. Throughout the duration of the study, as participants achieved more success (having the green light on >80% of the time), the stringency of their target (the magnitude of the deviation) was reduced, making it more difficult. The goal was to have the green light on for 70-80% of the time, creating a balance of reward and challenge.

Following the 20-minute LoRETA neurofeedback training, participants completed a five-minute HRV biofeedback session. The same HRV biofeedback exercise was completed as described above (which included a five-minute guided breathing exercise at a rate of approximately six breaths per minute). This HRV biofeedback session counted as one of their two daily HRV biofeedback sessions, and was recorded in their log books.

3.2.3 EEG Collection and LoRETA Neurofeedback

EEG was collected using the eVox System (Evoke Neuroscience, New York, New York), which is a portable hardware and software system for measuring electrophysiological data and performing various biofeedback sessions (surface neurofeedback, LoRETA neurofeedback, and HRV biofeedback). The eVox system consisted of a laptop, an amplifier, a response button, and a 19-lead EEG cap. When using the system, the cap was placed on the participant so that the 19 electrodes were situated on the head according to the 10-20 International System for electrode placement (80). The cap was then connected to the amplifier, which measured the EEG and ECG data and wirelessly transmitted them to the laptop. This setup was utilized for the LoRETA neurofeedback and also the EEG data collection.

3.2.4 Driving Simulator Collection

Performance on the CDS-200 DriveSafety™ simulator was collected and stored from the entire drive, with metrics collected at 50 Hz. This included vehicle speed, heading, and position within the lane. In addition, information was collected during each scripted event (e.g. the unexpected pedestrian crossing onto the roadway). Data collected also included metrics such as the distance to objects in the scripted events, and activation of the steering wheel, brake and gas pedal.

3.3 Data Analysis

3.3.1 RPQ and GAD

Total scores on the GAD for each participant were summed and change from baseline to follow-up was calculated. Comparisons of this change were analyzed between the intervention, PPCS control, and healthy control groups using a one-way analysis of variance (ANOVA). RPQ outcomes were tallied as two scores, similarly to previous research (41). The headache, nausea and dizziness scores were tallied, and the remaining

questions were tallied separately. The statistical significance of differences from baseline to follow-up between the three participant groups in both RPQ sub scores were assessed using one-way ANOVAs.

3.3.2 Driving Simulation Task

Three parameters were assessed during the driving simulation, including the reaction time for two of the specific scripted events (the unexpected pedestrian crossing and the car pulling out in front of the driver's simulated vehicle). Reaction times were assessed by evaluating the time difference between the start of the hazardous event and when the participant applied pressure to the brake or suddenly changed their lane deviation (i.e. swerving). Additionally, average lane deviation was calculated using the magnitude of deviation from the center of the lane at 50 Hz throughout the drive. This was measured in meters, and averaged over the span of the participant's drive. The statistical significance of differences from baseline to follow-up between the three participant groups were analyzed using a one-way ANOVA.

3.3.3 HRV and EEG

HRV was represented by the SDNN parameter (48). SDNN was expressed as a change from baseline to follow-up, and analyzed using a one-way ANOVA.

Participants' EEG results included the z-scores of the EEG amplitude for frequencies between 2 and 30 Hz at all 47 Brodmann areas (83). This yielded a rich data set with a total of 1288 EEG parameters per participant. Brodmann areas with the most deviation (12 areas maximum) were identified for all participants in the initial assessment, and were the chosen intervention target areas. Mean changes from baseline to follow-up within the designated target Brodmann areas, at all frequencies (2-30 Hz), were calculated. The statistical significance of differences from baseline to follow-up between the three participant groups were analyzed using a one-way ANOVA.

3.3.4 Statistical Analysis

All statistical analyses were performing using commercial software (SPSS 25, IBM Corp., Armonk, NY). All one-way ANOVA analyses followed the same protocol. Outliers were assessed using boxplots, and identified outliers were considered on a case-by-case basis. Normality of the distribution was assessed using a Shapiro-Wilks test. Levene's statistic was used to evaluate homogeneity of variances, and if the threshold for homogeneity of variances was not met, a Welch ANOVA and Games-Howell post hoc was used. If the homogeneity of variances assumption was met, a Tukey post hoc was used. The threshold for significance was set at $p = 0.05$ for all tests. Normality of distribution and homogeneity of variances are assumed unless otherwise stated.

4 Results

4.1 Compliance

Participants in the intervention group attended 88% of their LoRETA neurofeedback sessions (21 ± 2.56; the 25th, 50th, and 75th percentiles were 18.5, 22 and 23, respectively). The range extended from a low of 17 (one participant) to a maximum of 24 (two participants). Additionally, participants on average completed 86% of their HRV sessions (96.71 ± 10.14; the 25th, 50th, and 75th percentiles were 86, 99, and 106, respectively). The range extended from a low of 83 (two participants) to a maximum of 111 (one participant).

4.2 GAD and RPQ

Each group's average change in GAD scores decreased from baseline to follow-up (Figure 1). There were no differences (F = 0.528, p = 0.597) between groups, but there was a large amount of variability in the change data. This variability reflects that some of the participants in each of the groups showed no change or improvements while others showed decrements (Figure 2). Additionally, the remaining RPQ measures parameter identified no significant differences between groups (F = 0.090, p = 0.914; Figure 3).

The one-way ANOVA revealed that there were statistically significant differences in headache, nausea, and dizziness between the three groups (F = 10.088, p = 0.001). Post-hoc testing showed that the healthy control group had significantly greater decreases than the intervention group (p = 0.003) and the PPCS control group (p = 0.001). The difference between the intervention group and the PPCS control group was not significant (p = 0.935; Figure 5). There was also a large amount of variability in both RPQ parameter measures, therefore individual measures for remaining RPQ measures, along with headache, nausea, and dizziness, are provided (Figure 4 and Figure 6, respectively).

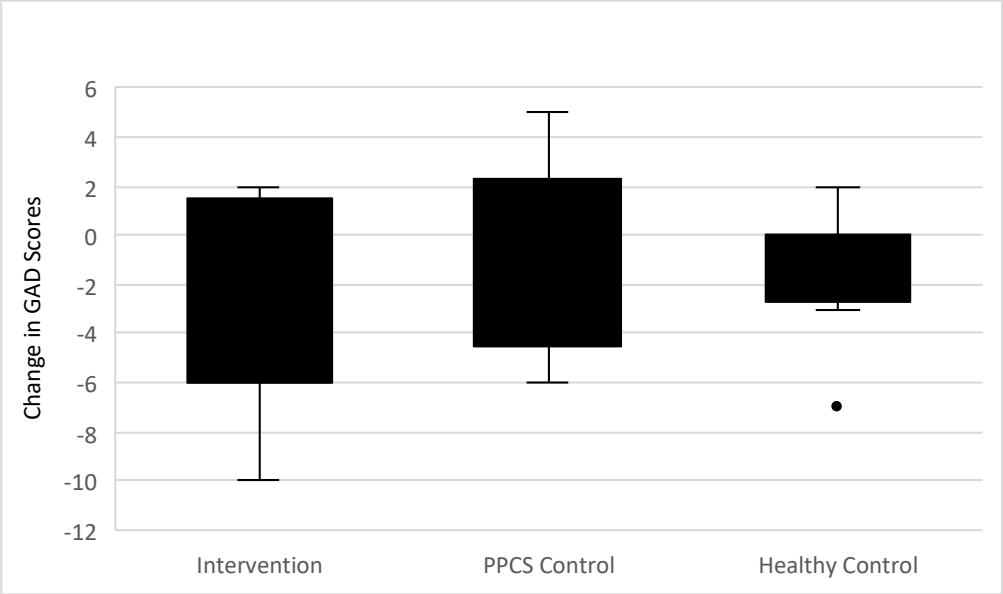

Figure 1. Average change in GAD scores between groups. Boxes reflect the interquartile range, whiskers reflect the minimum and maximum values, and dots represent outliers.

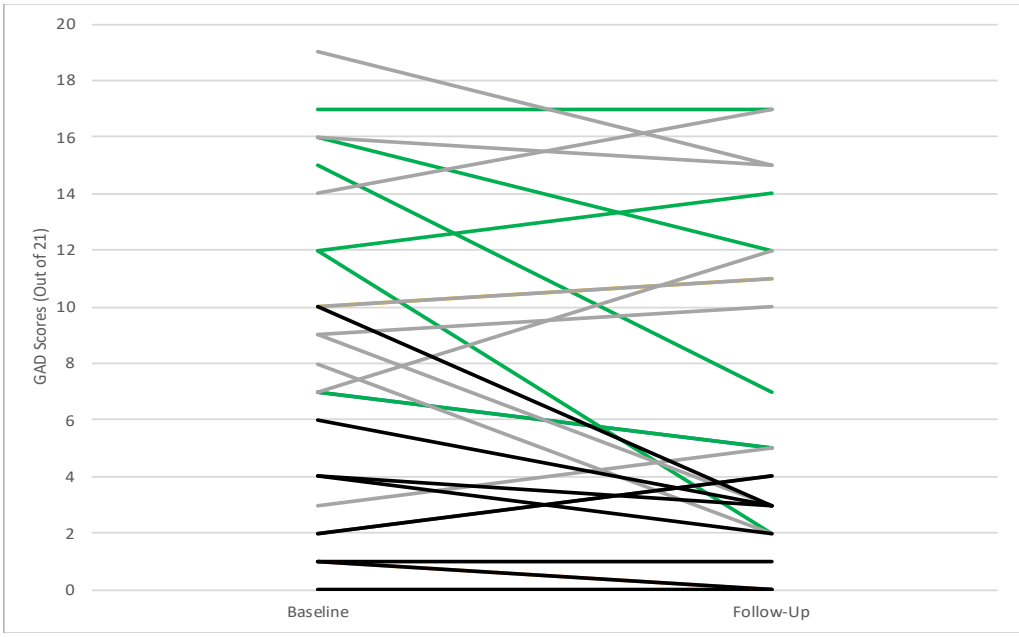

Figure 2. GAD Scores for the individual participants. Green indicates participants in the intervention group, grey indicates PPCS controls, and black indicates healthy controls.

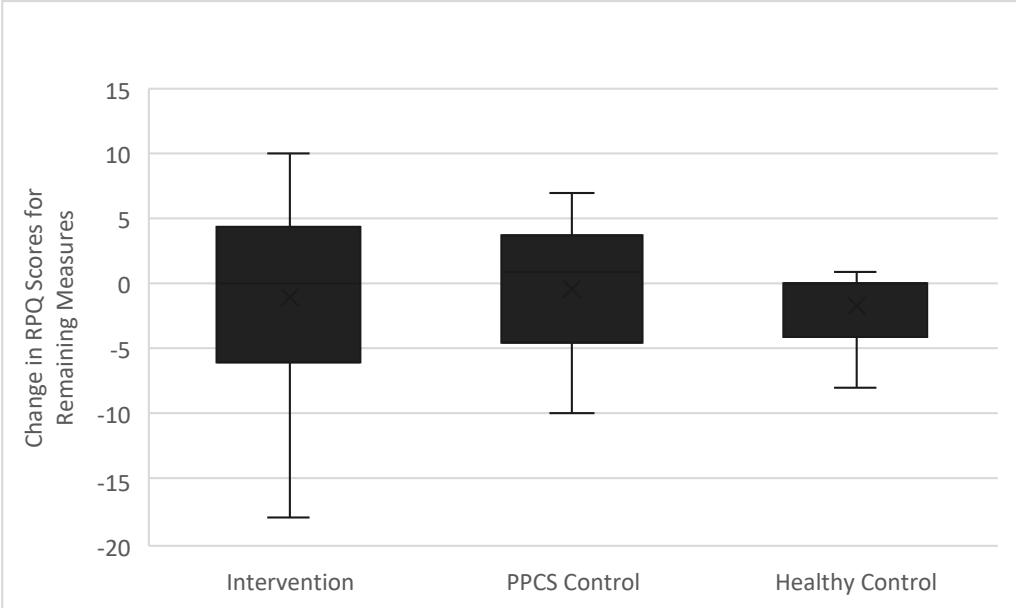

Figure 3. Average change in remaining RPQ scores between groups. Boxes reflect the interquartile range, whiskers reflect the minimum and maximum values, and dots represent outliers.

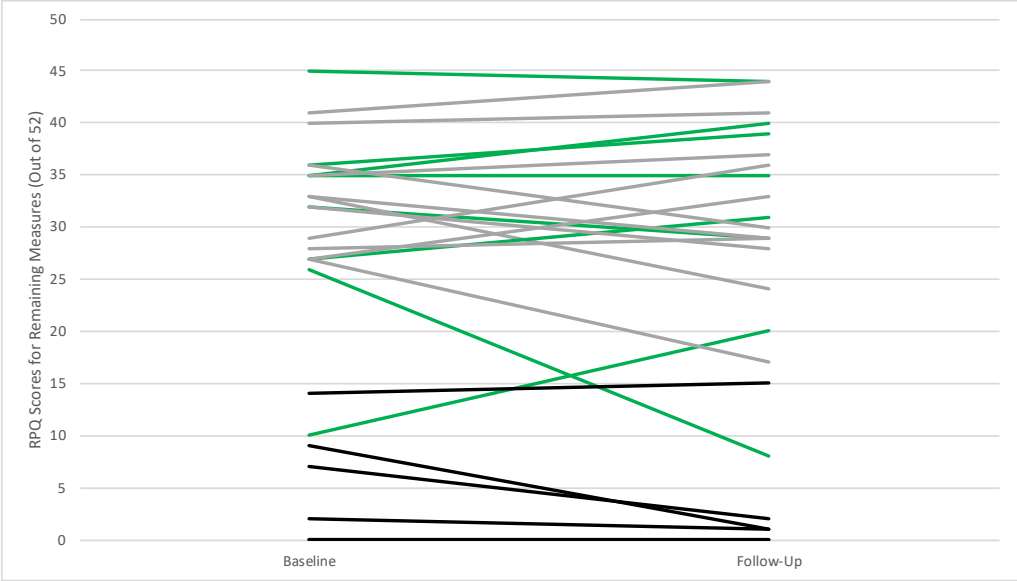

Figure 4. RPQ Scores for the individual participants on the remaining items. Green indicates participants in the intervention group, grey indicates PPCS controls, and black indicates healthy controls.

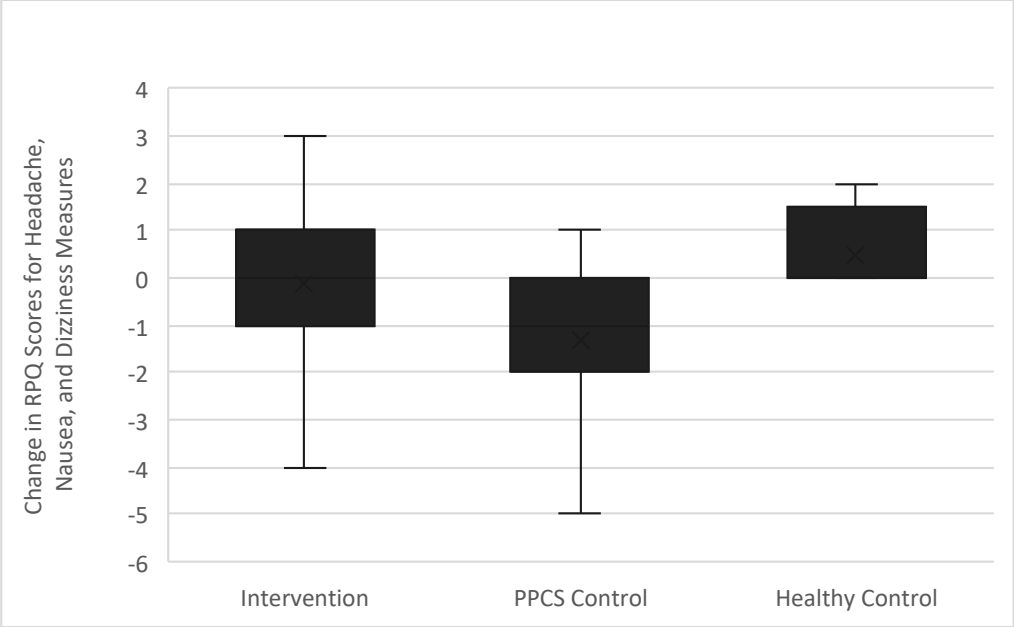

Figure 5. Average change in headache, nausea, and dizziness RPQ scores between groups. Boxes reflect the interquartile range, whiskers reflect the minimum and maximum values, and dots represent outliers.

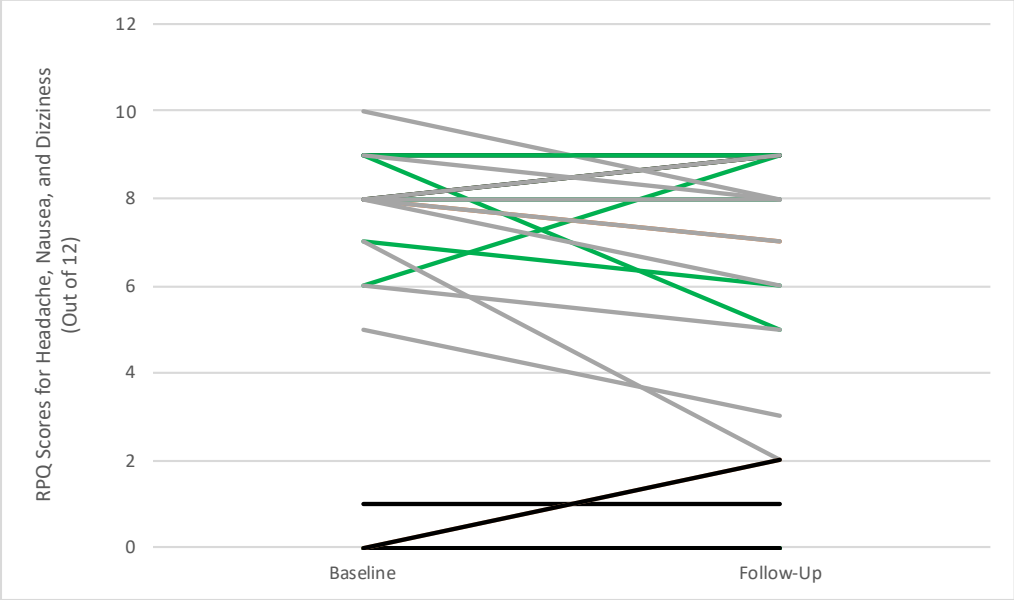

Figure 6. RPQ Scores for the individual participants on headache, nausea, and dizziness. Green indicates participants in the intervention group, grey indicates PPCS controls, and black indicates healthy controls.

4.3 Driving Simulation

Ten participants were involved in a collision during their driving simulator task. Eight collisions occurred in the initial assessment (two from the intervention group, four from the PPCS control group, and two from the healthy control group) and two occurred in their follow-up assessment (both from the PPCS control group). Accordingly, full drive metrics were not available for some participants. This resulted in the analysis of changes in reaction time to a vehicle pulling out in front of the participant in five intervention participants, five PPCS participants, and four healthy controls. Analysis revealed a lack of homogeneity of variances ($p = 0.024$), so a Welch ANOVA was performed. This analysis identified that there were no significant group differences ($F = 2.223$, $p = 0.167$) between the intervention group (-0.93 s ± 1.03, 95% CI = -1.89, 0.03), the PPCS control group (-0.01 s ± 0.43, 95% CI = -0.40, 0.39) and the healthy control group (-0.37 s ± 0.59, 95% CI = -0.87, 0.48).

The participants that were involved in collisions also effectively reduced the number of participants that were exposed to the pedestrian walking out scripted event. The reaction time in response to the pedestrian walking out in front of the vehicle was analyzed in six intervention participants, eight PPCS control participants, and seven healthy controls. The intervention group had an average reduced reaction time of -0.51 s ± 0.74 (95% CI = -1.29, 0.27), the PPCS control group had an average reduced reaction time of -0.31 s ± 0.70 (95% CI = -0.90, 0.27) and the healthy control group had an average reduced reaction time of -0.20 s ± 0.42 (95% CI = -0.99, 0.25). There were no statistically significant differences between groups ($F = 0.144$, $p = 0.867$). Lastly, there was a trend towards significant differences in mean lane deviation change between groups ($F = 3.102$, $p = 0.067$). The intervention group increased by -0.03 m ± 0.08 (95% CI = -0.04, 0.11), the PPCS control group increased by 0.10 m ± 0.10 (95% CI = 0.03, 0.19) and the healthy control group decreased by -0.01 m ± 0.11 (95% CI= -0.11, 0.09).

4.4 HRV

Initial and follow-up SDNN measures were compared between groups, with no significant differences between groups identified ($F = 0.267$, $p = 0.768$). The intervention group had an average SDNN decrease of -0.86 ms ± 16.27 (95% CI = -15.90, 14.18), while the PPCS control group had an average decrease of -7.79 ms ± 17.10 (95% CI = -20.92, 5.37) and the healthy control group had an average decrease of -4.71 ms ± 22.83 (95% CI = -25.83, 16.40).

4.5 EEG

One extreme outlier was identified in the healthy control group, therefore their EEG assessments were excluded from analysis. This approach was similar to other researchers (84). Differences in EEG did not have homogeneity of variances ($p = 0.04$). The Welch ANOVA identified a significant difference between groups ($F = 23.262$, $p < 0.005$). The intervention group had significantly greater normalization of their EEG in the target areas (smaller z-score deviations) than the PPCS control group ($p < 0.0005$). There were no significant differences between the PPCS control group or the intervention group and the healthy control group ($p = 0.448$ and 0.113, respectively; Figure 7).

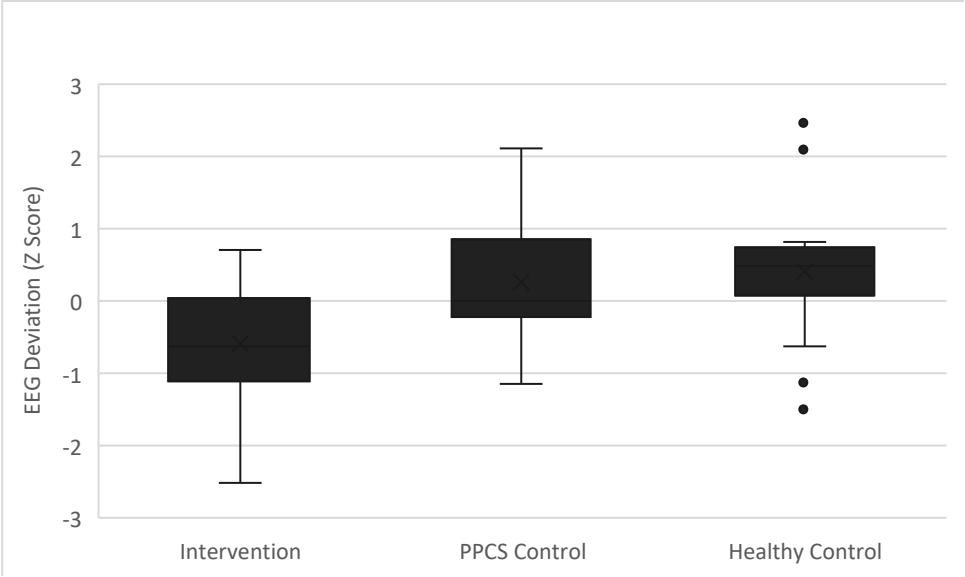

Figure 7. Average change in the normalized EEG z-score deviations between groups. Boxes reflect the interquartile range, whiskers reflect the minimum and maximum values, and dots represent outliers.

5 Discussion

Our intervention implemented a combination of LoRETA neurofeedback and HRV biofeedback in individuals with PPCS, and compared a multitude of outcome measures to participants with PPCS that did not receive the intervention, and a healthy control group. Individuals that received the intervention exhibited reduced EEG z-score deviations compared to the PPCS control group. Individuals in the intervention group also reported frequency and/or severity reductions in headache, nausea, and dizziness compared to the healthy control group. However, there were also differences between the PPCS control group and the healthy control group. For example, the PPCS control group's remainder RPQ scores showed less of a change in comparison to the healthy control group, likely reflecting functional impairments in participants with PPCS compared to healthy controls. There were also no statistically significant differences in GAD scores, driving simulation performance, or HRV between the three groups. Therefore, our findings support our hypothesis that LoRETA neurofeedback and HRV biofeedback contribute to reducing EEG z-score deviations.

Some research has identified that EEG z-scores can represent difficulties balancing concentration and relaxation (85). This lack of flexibility is problematic because it can result in wasted energy, or an inability to generate energy for an upcoming task. LoRETA neurofeedback evaluates the function of specific brain areas, enabling determination of the link between symptoms and brain function. For example, Brodmann area 10 is responsible for concentrating on one's own thoughts or paying attention to the external environment (86). This was a common neurofeedback target area for the participants with PPCS in this thesis, which may reflect the concentration difficulties that are typical in individuals with a concussion (14). Therefore, a reduction in EEG z-score deviations may have important practical implications. For example, the subset of study participants that showed reductions in z-score deviations also showed congruous changes in their concussion symptom scores.

We observed reduced EEG z-score deviations in the intervention group compared to PPCS controls, but these EEG changes were not associated with reduced PPCS, as

hypothesized. However, we did observe a large amount of variation in the subjective assessment outcomes between individuals. When interpreted clinically, this is important because it represents a disparity in the effectiveness this intervention; some participants experienced a reduction in symptoms, while others experienced an increase. This was also noted in the PPCS control group, and further supports the individuality of each person with PPCS (2). Therefore, similarly to many other PPCS rehabilitation practices, this intervention does not appear to be effective for everyone with PPCS (87, 88). Research regarding commonalities between responders would help indicate patients who would most likely benefit from this treatment.

Similarly to PPCS symptoms, reductions in EEG z-score deviations were not associated with improvements in driving performance, such as reaction time or lane deviation. But, the intervention group did exhibit a smaller magnitude increase in the average lane deviation compared to the PPCS control group. The magnitude of lane deviation in the intervention group was more similar to the healthy control group than the PPCS control group; this trend approached statistical significance. The intervention group also exhibited a trend towards decreased reaction time to respond during both of the scripted events: when the pedestrian walked in front of the car, and when the car pulled out in front of the participant, though these changes were not statistically significant. When applied to actual driving, decreases in reaction time may reduce the risk of a collision (89). Therefore, larger studies are encouraged in order to definitively evaluate the effectiveness of this intervention on driving reaction time. It should also be noted that the confidence intervals were large for each driving simulator parameter, which further indicates that there was a large amount of inter-individual variation in the effectiveness of this intervention.

Despite HRV training, there were no significant differences in SDNN between groups, and the 95% CIs indicated that the changes in SDNN between baseline and follow-up assessments for all of the groups were also not significant. But this does not necessarily indicate that the intervention did not have any effect on SDNN. Previous research has shown increases in SDNN during an intervention, but a return to normal at the end of treatment and at follow-up (90). Accordingly, the participants in the intervention group

may have exhibited changes during the intervention that reverted at the end of the study. Additionally, the intervention group did exhibit a trend toward attenuated SDNN reduction compared to both groups of controls, with some individuals from the intervention group showing improvement. Once again, this metric reinforces the variability of this intervention's effectiveness.

The large variation in the effectiveness of this intervention between participants indicates that some individuals responded, and others did not. Accordingly, it is appropriate to evaluate the features of individual cases to further explore these divergent responses. This is especially true when each participant in both of the control groups exhibited a range of changes in the various outcome measures. Two specific cases from the intervention groups are presented below to illustrate the scope of the responses: one non-responder and one responder.

Example Non-Responder: Participant 338. This individual attended all of their LoRETA neurofeedback sessions (24 of 24) and reported that they completed most of their HRV sessions at home (71%). Following the eight-week intervention, this participant exhibited a small increase in SDNN (51 ms to 54 ms), which was moving in the direction of the minimum goal of 65 ms. They also exhibited an increase in deviation in four of the six identified Brodmann areas following the intervention (Figure 8). However, their subjective scores on the GAD and RPQ either showed minimal improvement or worsening following the intervention. Their total for headache, dizziness, and nausea decreased slightly from seven to six (out of a possible 12), while their remaining RPQ scores increased substantially from 10 to 20 (out of a possible 52). Finally, their GAD score increased from two to four (out of a possible 21).

Example Responder: Participant 331: In contrast, participant 331 mainly exhibited improvements in their outcome measures following the intervention. This participant attended 83% of their LoRETA neurofeedback sessions, and reported that they completed 95% of their HRV sessions. Following the eight-week intervention, their SDNN reduced from 28 ms to 24 ms, which is moving away from the minimum goal of 65 ms. They exhibited significantly reduced deviations in two of the four identified Brodmann areas

(Figure 9). But, their subjective scores all improved, with headache, nausea and dizziness decreasing from nine to five. Further, their remaining RPQ scores decreased from 26 to 8, and their GAD scores decreased from 12 to two. Anecdotally this participant reported that their symptoms decreased so much that they thought that it may be appropriate to reduce their anxiety medication.

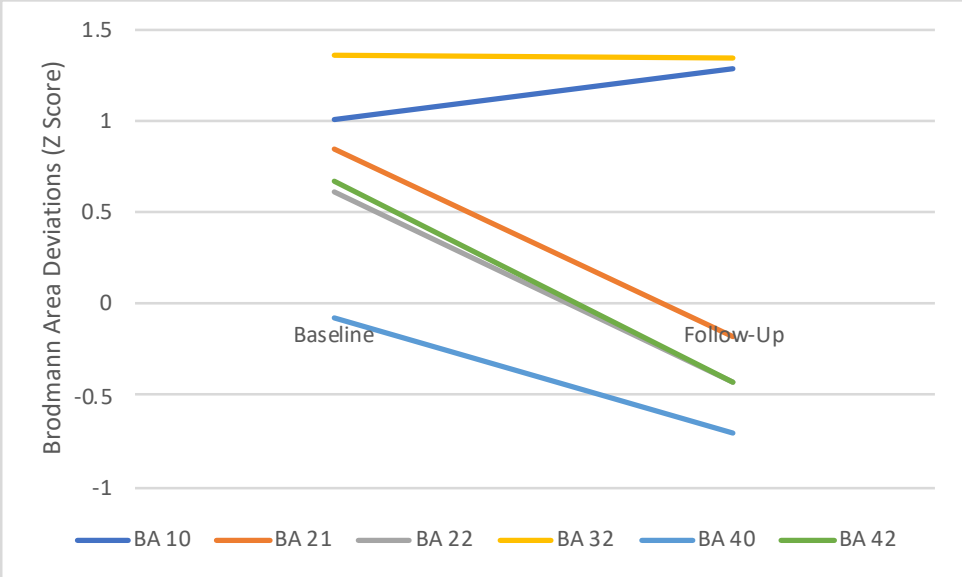

Figure 8. Individual Brodmann area (BA) baseline and follow-up deviation in Participant 338.

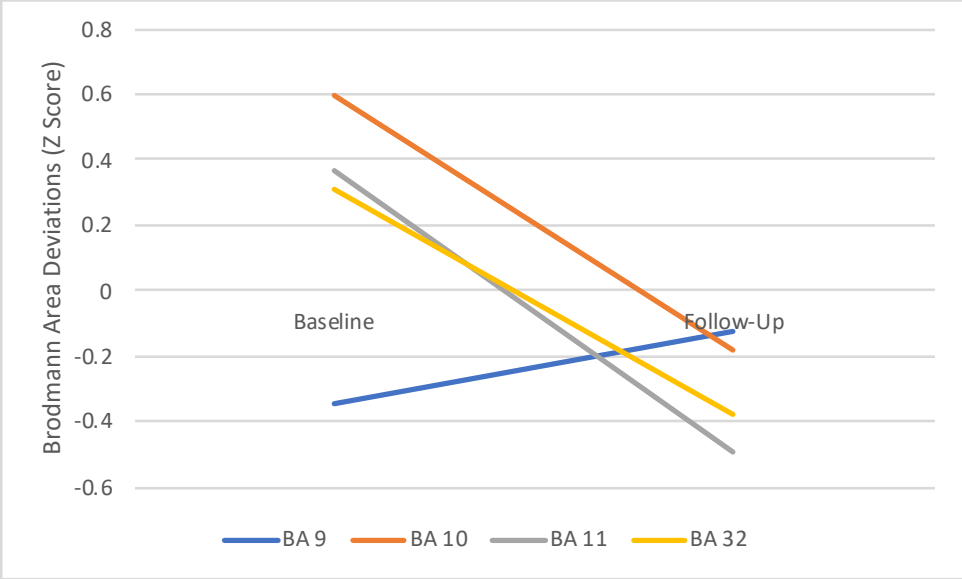

Figure 9. Individual Brodmann area (BA) baseline and follow-up deviation in Participant 331.

Although there was a large variation in the effectiveness of this intervention between participants, the concussed participants (intervention and PPCS control groups) also reported a diverse range of symptoms at baseline. Despite random assignment of concussed individuals into the intervention and control groups, the participants in the PPCS control group exhibited a greater range in the RPQ scores for the headache, nausea, and dizziness parameter, and a smaller range for the RPQ remaining measures parameter. These apparent differences in baseline subjective symptom scores may have influenced the effectiveness of the intervention. Furthermore, it is likely that there may be a complex relationship between the outcome measures in this study. For example, the intervention may have impacted symptoms, but not driving outcomes. Similarly, the intervention may have affected driving outcomes, but not SDNN. Other studies have used structural equation modeling to evaluate similar types of relationships (91), but this was not possible in the current experiment due to the relatively small number of participants.

This study is not without limitations. One limitation included the fact that we did not consider the influence of medications that our participants may have been taking. This study did not consider or evaluate the use of medication, or any changes that may have occurred while participating. A change in medication could have influenced the

participants' outcome scores. An additional potential limitation was that the number of LoRETA neurofeedback sessions differed between participants, based on compliance. Although providing neurofeedback three times a week was recommended by a licensed neurofeedback practitioner (92), some participants communicated that they experienced extreme fatigue (which contributed to reduced compliance). This may indicate that our choice of three neurofeedback sessions per week is not optimal. Previous biofeedback studies have used different number and frequencies of the neurofeedback sessions; one study used two to three LoRETA neurofeedback sessions per week, for 20 sessions (93) while another study used daily neurofeedback sessions (94). It is not clear whether the protocol in this thesis was optimal, and there does not appear to be any consensus on the best practices for LoRETA neurofeedback. Also, given the individuality of concussions, it may be that a patient-specific process is required rather than one protocol.

The neurofeedback in this thesis involved simultaneous training of up to 12 Brodmann areas. Other studies have used a similar criterion for defining which sites should be targeted for neurofeedback, but have trained a smaller number of concurrent sites (94). Some of the participants in the intervention group succeeded with the larger number of concurrent training sites, as illustrated with the responder case report, but some participants did not appear to successfully normalize their brain activities. It is not clear whether the relatively large number of sites used for the LoRETA neurofeedback in this thesis may have contributed to these divergent responses. As well, each participant used the same training sites throughout the entire intervention while other studies updated the neurofeedback training sites between sessions (94). While there are merits to maintaining consistent training sites, it may not be optimal for recovery.

Participants were responsible for reporting their participation in the HRV sessions, which can result in reporting inaccuracies. However, the investigators had three face-to-face interactions per week with all of the participants in the intervention group, which presumably may have increased compliance and reporting of the home HRV sessions.

Our parameterization of the RPQ scores is also a limitation. We divided the RPQ into two scores by tallying the headaches, dizziness and nausea scores separately from the

remaining 13 items. This approach is similar to previous research (41), but more recent research into the structure of the RPQ has identified that it may be better to quantify the RQP using a four factor model, clustered as vision, vertigo, mood/somatic and cognitive domains (95). It is unclear how our parameterization of the RQP scores may have influenced the findings.

This thesis only evaluated a subset of possible variables from the simulated driving performances. We focused on the reaction time in two of the five scripted events, and on the average lane deviation parameter. Research supports that reaction time is associated with individual accident involvement (96), supporting that this parameter has linkages to safety; however, our parameters may not reflect general aspects of driving skill. Furthermore, the lane deviation parameter that we analyzed, which evaluated average deviation over the span of the driving task, may not reflect safety-relevant behavior. For example, a scenario with one slow lane deviation in each lateral direction may have the same average lane deviation as a different scenario with more frequent and abrupt lane deviations, although the implications for safety are different (97). Therefore, abruptness of lane deviations, as well as number of lane deviations, may be more representative of at-risk driving behaviours. Furthermore, we did not evaluate driving behaviours such as visual scanning, that are also related to safety (24).

This study only looked at the immediate effects of the LoRETA neurofeedback and HRV biofeedback intervention. This approach is consistent with other neurofeedback studies (62, 63, 98). However, it is not known whether changes will remain in the longer-term. Alternatively, there may be delays before symptoms change. Some research has identified that concussion symptoms may have a delayed onset (2), and accordingly a reduction in symptoms could also be delayed. Therefore, future work is encouraged to investigate the prolonged effects of LoRETA neurofeedback and HRV biofeedback.

Considering this experiment as a whole, along with two illustrative case reports, it is clear that our intervention of combined LoRETA neurofeedback and heart rate variability biofeedback is promising for some individuals. We have not focused on identifying the

characteristics of individuals that respond, though that is an important avenue for future research.

6 Conclusions

In conclusion, interventions that combine LoRETA neurofeedback and HRV biofeedback are beneficial for some individuals with PPCS. It reduces EEG deviations, reduces driving simulation reaction time and lane deviation, and reduces symptoms in some individuals. The effectiveness of this intervention appears to differ between individuals, and further research is necessary to investigate whether it is possible to identify which individuals are likely to respond. It is well-understood that certain concussion symptoms are associated with prolonged duration of symptoms after a concussion (99), and so it may be that there are commonalities between individuals that respond to this type of intervention. Furthermore, studies that include longer follow-up times and larger populations should be performed to clarify and confirm the trends that have been identified in this study.

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Appendices

Appendix A: Western University Health Science Research Ethics Board Approval Notice

Western Research

Research Ethics

Western University Health Science Research Ethics Board
HSREB Full Board Initial Approval Notice

Principal Investigator: Dr. Jim Dickey
Department & Institution: Health Sciences\Kinesiology,Western University

Review Type: Full Board
HSREB File Number: 109760
Study Title: The effectiveness of neurofeedback and heart rate variability biofeedback for individuals with long-term post-concussive symptoms

HSREB Initial Approval Date: February 16, 2018
HSREB Expiry Date: February 16, 2019

Documents Approved and/or Received for Information:

Document Name	Comments	Version Date
Revised Western University Protocol	Version 12	2018/02/07
Revised Letter of Information & Consent	LOI for Controls Version 6	2018/02/07
Revised Letter of Information & Consent	LOI for Intervention Version 10	2018/02/07
Recruitment Items	recruitment poster - intervention arm	2017/11/20
Recruitment Items	recruitment poster - control group	2017/11/20
Advertisement	Recruitment Email	2017/08/30
Other	Generalized Anxiety Disorder Scale	2017/08/30
Other	Rivermead Post Concussion Questionnaire	2017/08/30
Other	At-Home HRV Log	2017/08/30
Other	Driving Simulator Evaluation Form	2017/08/31

The Western University Health Science Research Ethics Board (HSREB) has reviewed and approved the above named study, as of the HSREB Initial Approval Date noted above.

HSREB approval for this study remains valid until the HSREB Expiry Date noted above, conditional to timely submission and acceptance of HSREB Continuing Ethics Review.

The Western University HSREB operates in compliance with the Tri-Council Policy Statement Ethical Conduct for Research Involving Humans (TCPS2), the International Conference on Harmonization of Technical Requirements for Registration of Pharmaceuticals for Human Use Guideline for Good Clinical Practice Practices (ICH E6 R1), the Ontario Personal Health Information Protection Act (PHIPA, 2004), Part 4 of the Natural Health Product Regulations, Health Canada Medical Device Regulations and Part C, Division 5, of the Food and Drug Regulations of Health Canada.

Members of the HSREB who are named as Investigators in research studies do not participate in discussions related to, nor vote on such studies when they are presented to the REB.

The HSREB is registered with the U.S. Department of Health & Human Services under the IRB registration number IRB 00000940.

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Appendix B: Generalized Anxiety Disorder Scale

The Generalized Anxiety Disorder 7-Item Scale

Over the last 2 weeks, how often have you been bothered by the following problems?	**Not at all**	**Several Days**	**More than half the days**	**Nearly every day**
1. Feeling nervous, anxious, or on edge	0	1	2	3
2. Not being able to stop or control worrying	0	1	2	3
3. Worrying too much about different things	0	1	2	3
4. Trouble relaxing	0	1	2	3
5. Being so restless that it is hard to sit still	0	1	2	3
6. Becoming easily annoyed or irritable	0	1	2	3
7. Feeling afraid as if something awful might happen	0	1	2	3

Total Score: ☐ = **Add Columns** _____+ _____+_____

If you checked off any problems, how difficult have these problems made it for you to do your work, take care of things at home, or get along with other people?

Not at all	**Somewhat difficult**	**Very difficult**	**Extremely Difficult**
_____	_____	_____	_____

Appendix C: Rivermead Post-Concussion Symptoms Questionnaire

The Rivermead Post-Concussion Symptoms Questionnaire*

After a head injury or accident some people experience symptoms which can cause worry or nuisance. We would like to know if you now suffer from any of the symptoms given below. As many of these symptoms occur normally, we would like you to compare yourself now with before the accident. For each one, please circle the number closest to your answer.

0 = Not experienced at all
1 = No more of a problem
2 = A mild problem
3 = A moderate problem
4 = A severe problem

Compared with before the accident, do you now (i.e., over the last 24 hours) suffer from:

Headaches	0	1	2	3	4
Feelings of Dizziness	0	1	2	3	4
Nausea and/or Vomiting	0	1	2	3	4
Noise Sensitivity, easily upset by loud noise	0	1	2	3	4
Sleep Disturbance	0	1	2	3	4
Fatigue, tiring more easily	0	1	2	3	4
Being Irritable, easily angered	0	1	2	3	4
Feeling Depressed or Tearful	0	1	2	3	4
Feeling Frustrated or Impatient	0	1	2	3	4
Forgetfulness, poor memory	0	1	2	3	4
Poor Concentration	0	1	2	3	4
Taking Longer to Think	0	1	2	3	4
Blurred Vision	0	1	2	3	4
Light Sensitivity, Easily upset by bright light	0	1	2	3	4
Double Vision	0	1	2	3	4
Restlessness	0	1	2	3	4

Are you experiencing any other difficulties?

1. _____	0	1	2	3	4
2. _____	0	1	2	3	4

*King, N., Crawford, S., Wenden, F., Moss, N., and Wade, D. (1995) J. Neurology 242: 587-592

06/23/08

Curriculum Vitae

Name:	Marquise M. Bonn
Post-secondary Education and Degrees:	University of Western Ontario London, Ontario, Canada 2011-2015 B.Sc. Kinesiology 2016-2018 M.Sc. Kinesiology
Honours and Awards:	Western Scholarship of Distinction 2011 OUA Academic Achievement Award 2014 OUA Academic Achievement Award 2015
Related Work Experience	Teaching Assistant University of Western Ontario 2016-2018

Presentations

Bonn, Marquise M.; Dickey, James P.; Humphreys, Dave, Thompson, James W., Wolfe, Dalton L., McGuire, Shannon (2017). Proposed study evaluating the effectiveness of neurofeedback and heart rate variability biofeedback for individuals with long-term post-concussive symptoms. Bodies of Knowledge, oral presentation, Toronto, May 11-12.

Bonn, Marquise M., Harriss, Alexandra, Dickey, James P (2018). The effects of subconcussive impacts on heart rate variability in female youth soccer players. Experimental Biology, poster presentation, San Diego, April 21-25.