Chapter

# Impact of Biofeedback Interventions on Driving Performance in Individuals with Persistent Post-Concussive Symptoms

*Marquise M. Bonn, Liliana Alvarez, James W.G. Thompson and James P. Dickey*

## Abstract

Low resolution electromagnetic tomography (LoRETA) neurofeedback and heart rate variability (HRV) biofeedback may improve driving ability by enhancing attention, impulse control, and peripheral vision, and reducing stress. However, it is unclear whether combined LoRETA neurofeedback and HRV biofeedback can improve driving performance for individuals experiencing persistent post-concussive symptoms (PPCS). In this study, seven individuals with PPCS completed an eight-week LoRETA neurofeedback and HRV biofeedback intervention. Changes in participants' simulated driving performance and self-reported symptoms were measured and compared to two control groups: individuals with PPCS (n = 9), and healthy control participants (n = 8). Individuals in the intervention and PPCS control groups reported reduced PPCS severity ($p < .05$) compared to healthy control participants. Interestingly, individuals in the intervention group responded variably. These results indicate that more research is necessary to identify the subgroup of individuals that respond to LoRETA neurofeedback and HRV biofeedback and confirm these preliminary results.

**Keywords:** concussion, persistent post-concussion symptoms, neurofeedback, biofeedback, driving

## 1. Introduction

A concussion is defined as a mild traumatic brain injury 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 [1]. Most concussions resolve spontaneously, but some studies indicate that as many as 43% of individuals continue to experience persistent and disabling impairments months after their injury [2]. Persistent post-concussive symptoms (PPCS) refer to the lack of clinical recovery within 10–14 days for adults, and within four weeks for children [1]. As described in a recent review article [3], there is a lack

of consensus about numerous issues related to PPCS including causation. However, considering predisposing, precipitating, and perpetuating factors appears to be a fruitful approach [4]. Nevertheless, PPCS are problematic because they decrease quality of life. For example, individuals with PPCS have reduced social interactions, difficulty continuing previously enjoyed past-times, and struggle resuming pre-injury physical capabilities, employment, and daily tasks [5]. Driving can also be impacted, with one study reporting that 93% of individuals with PPCS experience at least one difficulty that negatively impacted their driving [6].

Driving requires the integration of motor, cognitive, perceptual, and sensory skills in response to environmental information [7]. Sustaining a concussion may impact these driving abilities and result in impaired driving performance [6, 8, 9]. Furthermore, individuals who experienced a concussion but are no longer symptomatic exhibit impaired driving performance when assessed in a driving simulator [10]. Such impairments are also evident in on-road driving, where the number of motor vehicle collisions for persons six to nine years following a traumatic brain injury are more than double the reported average [11]. Accordingly, treatments are necessary to reduce the risk while driving following a concussion.

There are several challenges to treating individuals with PPCS. Individualized treatment plans that target physical and psychosocial symptoms are recommended [1, 12]. However, treatments focused on symptoms do not necessarily address their root cause, which may be altered brain physiology. Biofeedback approaches are designed to address physiological injury and may improve functional performance [13].

Heart rate variability (HRV) describes the natural beat-to-beat variability in heart rate. It represents autonomic function and sympathetic-parasympathetic balance [14]. HRV is altered in individuals suffering concussions [15] and PPCS, including hyperactive sympathetic activity and reduced parasympathetic activity [16]. HRV biofeedback is designed to repair sympathetic-parasympathetic balance, as well as baroreflex activity [17]. It improves cognitive functioning and emotional regulation in some individuals experiencing a brain injury [18]. It may also contribute to improved attention [19] and problem-solving abilities [20], and enhanced executive functioning [21]. HRV biofeedback may also reduce symptoms and improve mood in individuals with PPCS [22, 23].

HRV biofeedback is often used in conjunction with electroencephalograph (EEG) biofeedback (neurofeedback) since neurofeedback can also influence the neuroanatomical networks and structures that affect HRV [13, 24, 25]. Neurofeedback has evolved from measuring and training brain activity using surface electrodes, to more robust methods including source localization neurofeedback. This form of neurofeedback is known as low-resolution electromagnetic tomography (LoRETA) neurofeedback [26]. LoRETA neurofeedback allows the participant to see the amplitude of electrical activity at specific brain regions in real time, and they can therefore self-regulate this electrical activity [26]. It is non-invasive and enables individualized rehabilitation. Individualization is important as it is one of the biggest limitations of traditional brain injury interventions [12].

LoRETA neurofeedback corrects functional deficiencies in individuals with major depressive disorder [27]. When combined with HRV biofeedback, the intervention improves both depression and anxiety symptoms [28], which may contribute to improved driving performance and reduced driving errors [29, 30]. Additionally, the combined intervention may help individuals perceive, attend, and interpret a stimulus [7] by improving disorders of attentional processing [31, 32]. Following the interpretation of a stimulus, the driver must plan an action to react to a stimulus, and then execute the action [7]. LoRETA neurofeedback and HRV biofeedback may improve planning by improving executive function [32],

and may improve execution by increasing motor [33] and impulse control [31]. Planning an action can also be improved through previous experience [7], and this may be improved through LoRETA neurofeedback and HRV biofeedback by way of improving working memory [34].

Therefore, this chapter describes a research study designed to determine whether HRV biofeedback in combination with LoRETA neurofeedback showed promise as an intervention to reduce self-reported concussive symptoms and improve simulated driving performance in individuals experiencing PPCS.

## 2. Materials and methods

Thirty-one individuals were recruited to participate in this study, which was approved by the Western University Health Science Research Ethics Board and registered with ClinicalTrials.gov (NCT03338036). Participants with PPCS had to be 18 years of age or older, experienced a clinically diagnosed concussion and completed a concussion rehabilitation program, and still experiencing ongoing symptoms. They also had to be fluent in English, hold a valid driver's license, and capable of using hand-held devices. Healthy participants had to be 18 years of age or older, and could not have experienced a concussion in the last two years. They also had to be fluent in English and hold a valid driver's license. All participants provided written informed consent.

Twenty-three individuals with PPCS were randomized into the intervention or active control group (11 in the intervention group and 12 in the PPCS control group). However, seven PPCS participants experienced a worsening of symptoms during the baseline testing and could not complete the driving simulator task, excluding them from participation. This resulted in seven participants in the intervention group (48.6 ± 14 years old, four females). The youngest participant in the intervention group was 30, while the oldest was 75. The PPCS control group had nine participants (54.7 ± 8 years old, six females), with the youngest being 37 and the oldest being 65. Lastly, there were eight healthy control participants (49.6 ± 16.5 years old, four females). The youngest healthy control participant was 25 while the oldest was 74.

### 2.1 Baseline and follow-up assessment

Participants were initially contacted via email about this study; their response prompted an informational email. They then met with a study investigator at the iMobile Research Lab at Western University, London, Ontario, Canada, 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 [35]. The electrodes 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 prior to attaching electrodes to both earlobes using clip electrodes; these sites acted as a reference. All leads used AFz as ground and passed through an amplifier (Evoke Neurosciences, New York, NY). Additionally, one electrode was taped to the participants chest, inferior to the left clavicle, to monitor their electrocardiogram.

The participant then completed a brain function assessment, including a three-minute resting EEG measurement with their eyes-closed. Afterwards, the participant completed a Rivermead Post-Concussion Symptoms Questionnaire

(RPQ) [36] and Generalized Anxiety Disorder 7-Item Scale (GAD-7) [37]. Next, they performed the driving simulation task on a CDS-200 DriveSafety™ simulator, which included a steering wheel and dash display from a Ford Focus, a gas and brake pedal, and three computer screens for displaying the environment around the vehicle. The simulator was adjusted for the participant's 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 task began with a simulator acclimation protocol including dimmed lights to reduce visual strain, temperature control in the simulator room (21° C) to ensure comfort, utilization of a fan to increase air flow around the participant, and three acclimation drives totaling seven minutes. These factors have been identified to mitigate simulator sickness [38]. The acclimation drives increased in complexity, starting with a straight drive while maintaining a speed of approximately 50 kph with no other vehicles on the road and low visual complexity of the scenario. The next acclimation drive required navigating a city block with four consecutive left-hand turns, and ended with a drive requiring four consecutive right-hand turns. The left-hand and right-hand turn scenarios were completed with few vehicles on the road, thus introducing real driving situations. For example, the participant had to wait for an oncoming car to drive through the intersection before completing a left-hand turn. Participants were offered breaks between simulator tasks as needed. They were also screened for symptoms of simulator sickness before and after each acclimation drive using the Adapted Motion Sickness Assessment Questionnaire [39], adapted to an 11-point scale as done in previous research [40]. Participants rated their feelings of sweatiness, queasiness, dizziness, and nausea on a scale from 0 (not at all) to 10 (severely).

Finally, participants performed one of two simulator drives. Both drives contained the same scripted events representing potentially hazardous situations: an unexpected pedestrian crossing the street in front of the car, and a car suddenly pulling out of a driveway in front of the participant. The scripted events were pseudorandomized across the two drives to control for any potential learning effect of the route. The drive was approximately 10 minutes in length. These drives have been used in other experiments, and were specifically designed to assess the driving performance of young adults [40, 41].

After eight weeks, all participants returned to complete another brain function assessment, RPQ and GAD-7, and driving simulator acclimation and drive. The final simulator drive was the alternate drive to their baseline assessment. For example, if they completed Drive 1 in their baseline assessment, then they completed Drive 2 in their follow-up assessment.

### 2.2 Intervention

Participants in the intervention group received an Android tablet (either a Craig 7 inch 1 GB 6.0 "Marshmallow" Tablet, New York, New York or a Samsung Galaxy Tab A 7 inch 8 GB 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. Participants in the intervention group were taught how to use the equipment, and instructed to 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 (Mindja, Evoke Neurosciences, New York, New York) on their tablet, and doing a 5-minute exercise in which they were cued to breathe at their resonant frequency [42]. 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 sessions were performed in a private room at Parkwood Institute in London, Ontario. Each LoRETA neurofeedback session was broken up into 10 exposures, each two-minutes in 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, as determined from their initial assessment. Each participant in the intervention group was scheduled to participate in three sessions per week (usually at the same time on Mondays, Wednesdays, and Fridays), for eight consecutive weeks. This resulted in a potential total of 24 LoRETA neurofeedback sessions and 112 HRV biofeedback sessions.

### 2.3 Data analysis

Total scores on the GAD-7 for each participant were summed, and the change from baseline to follow-up was calculated. These changes were compared between the intervention, PPCS control, and healthy control groups using a Kruskal-Wallis non-parametric analysis (SPSS 25, IBM Corp., Armonk, NY). RPQ outcomes were tallied as two scores, similarly to previous research [43]. The headache, nausea and dizziness scores were tallied together (RPQ-3), and the remaining questions were tallied separately (RPQ-13). The differences from baseline to follow-up between the three participant groups in both RPQ sub scores were also assessed using a Kruskal-Wallis analysis.

Driving simulation analysis focused on two scripted events (an unexpected pedestrian crossing and a car suddenly pulling out of a driveway), as these events challenged the participant's reactions. Three parameters were assessed for these events: reaction time, maximum brake applied and the distance from the event when the maximum brake was applied. Reaction times were quantified as 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). Maximum brake applied was indicated on a zero to one scale, with zero representing no braking and one representing the maximum brake application possible. Differences from baseline to follow-up between the three participant groups were analyzed using a non-parametric Kruskal-Wallis analysis.

## 3. Results

### 3.1 Compliance

Participants in the intervention group attended 88% of their LoRETA neurofeedback sessions (21 ± 2.6 of the 24 possible sessions; the 25, 50, 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 (96.7 ± 10.1 of the 112 possible sessions; the 25, 50, 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).

### 3.2 GAD-7 and RPQ

There were no significant differences in GAD-7 or RPQ-13 between the intervention, PPCS control, and healthy control groups (**Table 1**). There were

significant differences in RPQ-3 outcomes. Post-hoc analysis revealed significant differences between the intervention group and healthy control group ($p < .05$) and the PPCS control and healthy control groups ($p < .05$). The difference between the intervention and PPCS control group was not significant ($p = .83$). Furthermore, participants demonstrated variable responses, therefore individual measures are presented for GAD-7 (**Figure 1**), RPQ-3 (**Figure 2**), and RPQ-13 (**Figure 3**).

| Outcome | Intervention | PPCS Control | Healthy Control | *H* Statistic | *p* Value |
|---|---|---|---|---|---|
| GAD-7 (Median) | −2.3 | −0.6 | −1.5 | 0.94 | .62 |
| RPQ-3 (Median) | −1 | −3 | 5.5 | 12.02 | <.01* |
| RPQ-13 (Mean rank) | 13.2 | 13.0 | 16.2 | 0.88 | .65 |
| Car pull out reaction time (Mean rank) | 7.7 | 13.0 | 9.7 | 2.88 | .24 |
| Car pull out max brake (0–1; Median) | −.14 | 0.00 | −.05 | 0.97 | .62 |
| Car pull out distance at brake max (m; Median) | 2.47 | −2.70 | −0.65 | 3.66 | .16 |
| Pedestrian walk out reaction time (s; Median) | −0.48 | 0.53 | −0.08 | 1.19 | .55 |
| Pedestrian walk out max brake (0–1; Median) | 0.00 | −.03 | −.03 | 0.02 | .99 |
| Pedestrian walk out distance at brake max (Mean rank) | 12.3 | 10.0 | 9.1 | 1.05 | .59 |

**Table 1.**
*Statistical evaluations of the change in generalized anxiety disorder 7-item scale (GAD-7), Rivermead post-concussion symptoms questionnaire (RPQ), and driving outcomes from baseline to follow-up. *indicates statistical significance.*

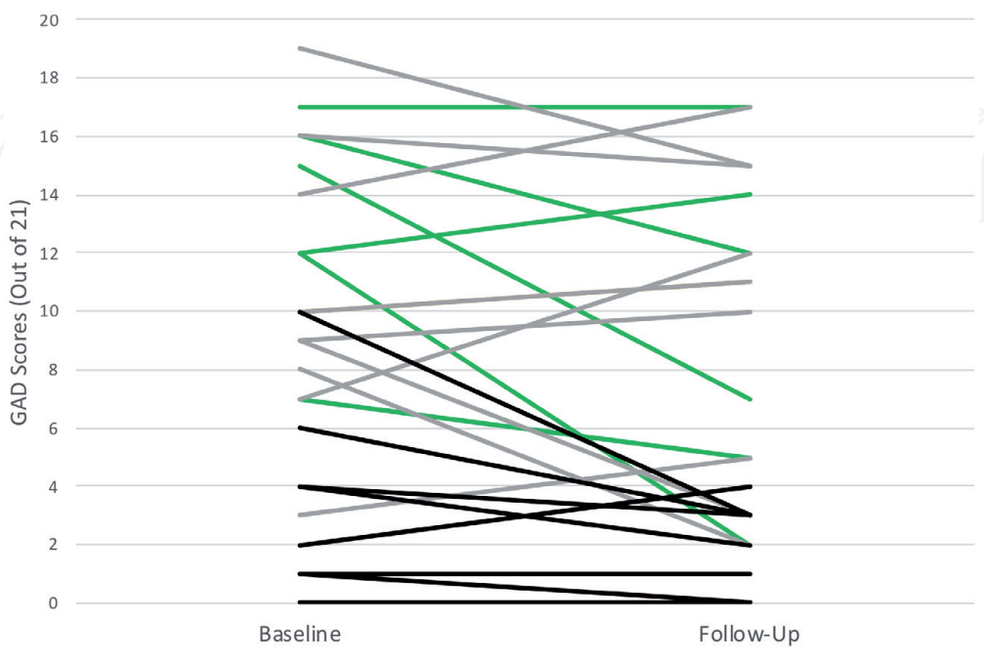


**Figure 1.**
*GAD-7 scores for individual participants. Green indicates participants in the intervention group, gray indicates PPCS controls, and black indicates healthy controls.*

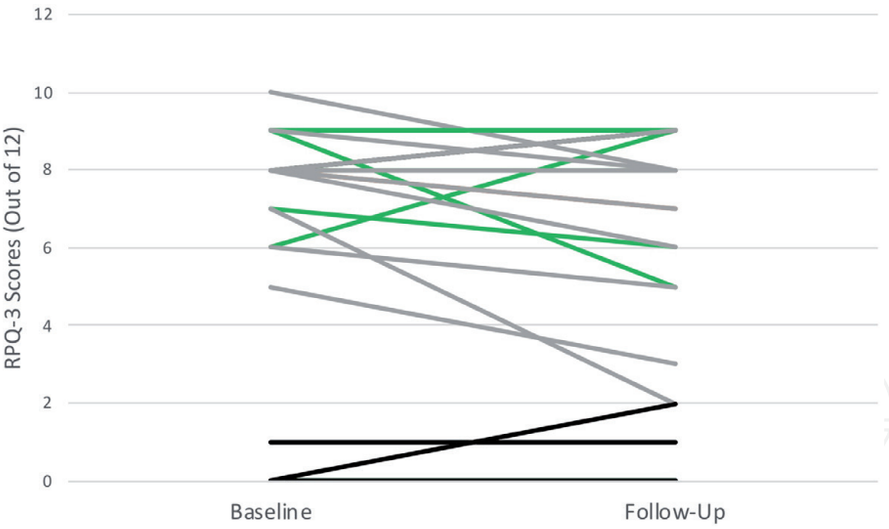


**Figure 2.**
*RPQ-3 scores for individual participants. Green indicates participants in the intervention group, gray indicates PPCS controls, and black indicates healthy controls.*

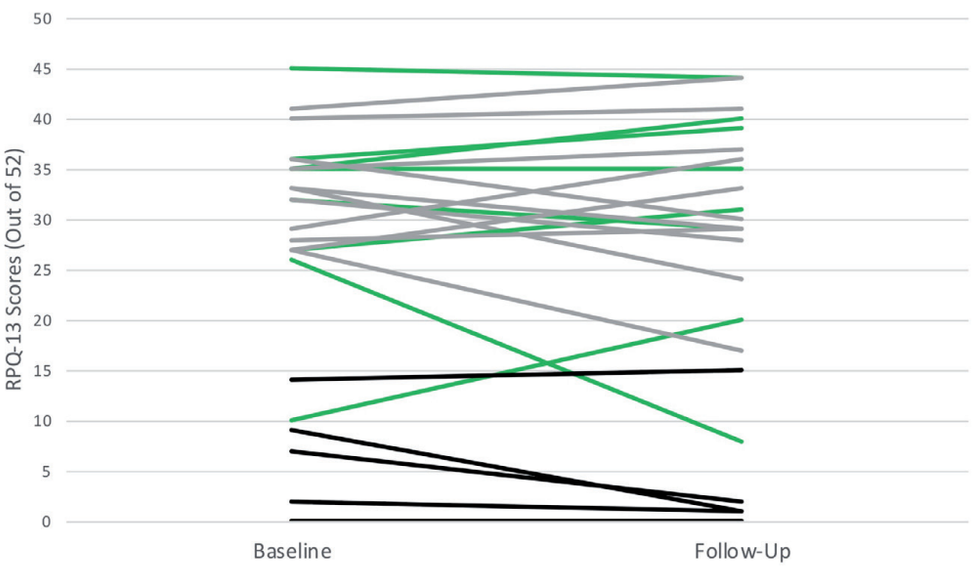


**Figure 3.**
*RPQ-13 scores for individual participants. Green indicates participants in the intervention group, gray indicates PPCS controls, and black indicates healthy controls.*

## 3.3 Driving simulation

Ten participants were involved in a collision during their driving simulator performances. Eight collisions occurred in the baseline assessment (two from the intervention group, two from the PPCS control group, and four from the healthy control group) and two occurred in their follow-up assessment (both from the PPCS control group). Collisions automatically terminated the simulation. Two collisions occurred after the scripted events. Accordingly, full drive metrics were not available for eight participants. The analysis of changes in reaction time to the car suddenly pulling out of the driveway were based on seven intervention participants, six PPCS control participants, and six healthy controls. There were no differences between groups in reaction time to the car suddenly pulling out, or their maximum brake effort or distance (**Table 1**).

Collisions also effectively reduced the number of participants that were exposed to the unexpected pedestrian crossing. The change in reaction time in response to

the unexpected pedestrian crossing was based on six intervention participants, seven PPCS control participants, and eight healthy controls. There were no differences between groups in their reaction time, maximum brake effort or distance to an unexpected pedestrian crossing (**Table 1**).

## 4. Discussion

Our intervention evaluated a combination of LoRETA neurofeedback and HRV biofeedback in individuals with PPCS, and compared concussive symptoms and driving performance to participants with PPCS that did not receive the intervention, and a healthy control group. Individuals in the intervention group reported improvements in RPQ-3 outcomes compared to the healthy control group. However, the PPCS control group also had reduced RPQ-3 outcomes compared to the healthy control group, and the difference between the intervention and PPCS control group was not significant. There were no statistically significant differences in GAD-7 scores or driving simulation outcomes (reaction time, maximum brake or distance at maximum brake) to the scripted events of the car suddenly pulling out of a driveway or the unexpected pedestrian crossing. Therefore, the results of this study indicate that LoRETA neurofeedback and HRV biofeedback did not reduce symptom number or severity, nor did it improve simulated driving performance. However, outcomes varied between participants. Emerging models evaluating the predisposing, precipitating, and perpetuating factors related to PPCS [4] may provide insights into the variable responses between participants, and should be considered in future investigations.

Previous research has shown that a single session of LoRETA neurofeedback results in acute changes in current densities in specific regions of the brain [27]. As well, previous intervention studies have indicated that LoRETA neurofeedback reduced symptoms in individuals with a brain injury [44, 45]. But, these studies tailored the LoRETA neurofeedback protocol for each individual. Furthermore, the target cerebral areas and training amplitudes also varied between studies based on the individual initial assessments. Despite our utilization of an initial EEG assessment, other factors could have been considered to inform cerebral area and amplitude selection, and further individualize our protocol.

Previous research has recommended considering initial symptom presentation when creating a LoRETA neurofeedback protocol to treat acute brain injuries [46]. Initial symptom presentation was difficult to attain in our study because participants were no longer in the acute phase of their injury. Therefore, this increased the risk of recall bias because of this population's increased likelihood for impaired memory recall [47]. However, it is unclear whether considering initial symptom presentation, current symptom presentation, or a combination may be more appropriate when creating a LoRETA neurofeedback protocol for individuals with PPCS. Secondly, the number of sessions should be based on the rate of improvement rather than a fixed number of sessions [46], which we chose to maintain for a consistent research protocol. The 24-session protocol was recommended by a licensed practitioner to balance intervention effects, research feasibility, and participant compliance. Lastly, consideration of persisting symptoms and their severity may further refine the intervention to increase participant's improvements. For example, there is a hyperbolic relationship between initial symptom presentation and number of neurofeedback sessions necessary [46], with increased initial symptoms requiring more neurofeedback sessions. Similarly, an increase in symptom persistence could increase the number of neurofeedback sessions required for improvement. Consideration of these three factors may have influenced the participants' responses to the intervention.

The lack of improvement in the driving simulation may have also been a result of the complex relationship between the outcome measures in this study. Outcomes (symptoms and driving simulation metrics) were evaluated independently, but there may not be a direct relationship between symptoms and driving simulation performance. Other studies have used structural equation modeling to evaluate similar types of relationships [48], but this was not possible in the current experiment due to the limited number of participants.

Individuals with a concussion or PPCS often experience executive dysfunction [47], which may be exhibited by inappropriate driving speed, following others too closely, or braking at inappropriate times [49]. Participants in the intervention group exhibited the greatest decreases in reaction times to the hazardous events (pedestrian walking out and car pulling out). Although these changes were not statistically significant, improved reaction times may indicate improved processing times, which is associated with fewer collisions [50]. Additionally, participants in the intervention group had the largest increases in distance from the hazardous event when they maximally applied the brake. They also exhibited the largest decrease in maximum brake effort when the car pulled out (although not statistically significant). These improvements also indicate increased driving safety, as increased distance and decreased brake effort indicate improved decision-making and ultimately improved executive function [49]. These safety improvements are particularly important for the PPCS population as their risk of collision may be higher when compared to the normal population [51].

The results of this study further indicate that individuals with PPCS require specialized driving evaluations, as previously identified [6, 9, 52, 53]. However, only half of physicians 'almost always' provide driving guidance following a concussion [54]. The lack of universally accepted procedures may be related to the absence of return-to-drive guidelines. Current clinical practice guidelines suggest that individuals who experience a concussion should not drive for 24 hours post-injury [55]. However, there are no guidelines for individuals driving with persistent symptoms, nor graded return to driving. This absence of clinical guidelines to assist physicians in making fitness to drive determinations in this population may increase the risk of collisions in individuals with PPCS. Additionally, 30% of physicians have stated that they do not have clear 'return-to-drive criteria' when evaluating fitness to drive in recently concussed individuals [54]. This further illustrates the need for research on the driving performance of individuals with PPCS, which can inform evidence-based return-to-drive guidelines. As indicated by this study, driving simulation research in this population is limited by the likelihood of simulator sickness, as occurred with seven of our recruited participants. This represents a barrier for completing this type of research. However, simulator sickness mitigation protocols can help reduce the incidence and improve retention.

Our study has shown some promising results, but does have some limitations. Most importantly, this study examined the effects of neurofeedback and HRV biofeedback on a small sample size. This represents a challenge with respect to both internal validity and generalizability [56]. For instance, our sample of participants may be biased towards high-functioning individuals that did not experience simulator sickness. Our study also did not consider medication usage that may have influenced participants' outcome scores [1]. Another potential limitation was that we did not consider driving experience. Although there were no significant differences between age groups, some individuals may have had more experience driving or more driving training. This could have resulted in differences in driving simulation performance prior to a brain injury. Additionally, although our parameterization of the RPQ is similar to previous research [43], other research indicates the RPQ can be quantified using a four factor model, clustered as vision, vertigo, mood/

somatic and cognitive domains [57]. It is unclear how our parameterization of the RPQ scores may have influenced the findings. Lastly, this study only looked at the immediate effects of the LoRETA neurofeedback and HRV biofeedback intervention. Although consistent with other neurofeedback studies [31, 58, 59], it is unclear whether short-term responses reflect long-term outcomes. Alternatively, there may be delays before symptoms change [1], and accordingly a reduction in symptoms could also be delayed.

This study is the first to systematically implement and evaluate the outcomes of a LORETA neurofeedback and HRV biofeedback protocol for civilians with PPCS. It is also noteworthy that this study evaluated the outcomes of LORETA neurofeedback and HRV biofeedback in individuals that completed a rehabilitation program and had ongoing PPCS; a population with symptoms that may be difficult to treat [47]. Considering the participant population, these results are especially valuable to healthcare practitioners because they include clinically relevant outcomes (i.e. self-reported symptoms and driving performance).

## 5. Conclusions

This study implemented an intervention involving a combination of LoRETA neurofeedback and HRV biofeedback for eight weeks, based on individual EEG baseline assessments. Eleven participants with PPCS were included in the intervention group (seven that finished the protocol), 12 in the PPCS control group (nine that finished the protocol), and eight healthy control participants. Considering the PPCS intervention group as a whole, this combined intervention did not improve symptoms or driving simulation performance. However, some of the individuals did show improvements. This may indicate that this intervention is effective for a subgroup of individuals with PPCS, or perhaps that the intervention needs to be further individualized to optimize participants' responses. Specifically, the nature of the symptoms, rate of improvement, and length of symptom persistence may need to be considered to individualize the protocol. The results of this study also emphasize the importance of evaluating fitness to drive following a concussion, as well as the need for return-to-drive guidelines for individuals experiencing symptoms following a concussion.

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## Conflict of interest

Dr. James Thompson is the Co-Founder of Evoke Neuroscience. Evoke Neuroscience donated the eVox EEG systems for this research, and the corresponding analyses. Dr. Thompson contributed to the research design, analysis and manuscript editing. All remaining authors have no conflict of interest to report.

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## Author details

Marquise M. Bonn[1], Liliana Alvarez[1], James W.G. Thompson[2] and James P. Dickey[1*]

1 Faculty of Health Sciences, Western University, London, Canada

2 Evoke Neuroscience Inc., New York, USA

*Address all correspondence to: jdickey@uwo.ca

## References

[1] McCrory P, Meeuwisse W, Dvorak J, Aubry M, Bailes J, Broglio S, et al. Consensus statement on concussion in sport-the 5th international conference on concussion in sport held in Berlin, October 2016. British Journal of Sports Medicine. 2018;**51**(11):838-847

[2] Voormolen DC, Cnossen MC, Polinder S, von Steinbuechel N, Vos PE, Haagsma JA. Divergent classification methods of post-concussion syndrome after mild traumatic brain injury: Prevalence rates, risk factors, and functional outcome. Journal of Neurotrauma. 2018;**35**(11):1233-1241

[3] Young G. Thirty complexities and controversies in mild traumatic brain injury and persistent post-concussion syndrome: a roadmap for research and practice. Psychological Injury and Law. 2020;**13**:427-451

[4] Rickards TA, Cranston CC, McWhorter J. Persistent post-concussive symptoms: A model of predisposing, precipitating, and perpetuating factors. Applied Neuropsychology: Adult.;2020; In press:1-111

[5] Emanuelson I, Andersson Holmkvist E, Björklund R, Stålhammar D. Quality of life and post-concussion symptoms in adults after mild traumatic brain injury: A population-based study in western Sweden. Acta Neurologica Scandinavica. 2003;**108**(5):332-338

[6] Bottari C, Lamothe M-P, Gosselin N, Gélinas I, Ptito A. Driving difficulties and adaptive strategies: the perception of individuals having sustained a mild traumatic brain injury. Rehabilitation Research and Practice. 2012;**2012**: Article ID 837301.

[7] Rizzo M, Kellison IL. The brain on the road. In: Marcotte TD, Grant I, editors. Neuropsychology of Everyday Functioning. New York, NY, US: Guilford Press; 2010. pp. 168-208

[8] Dumphy D, Zerpa C, Hoshizaki T, Weaver B, McKee D, Bédard M, et al. The effect of concussion on reaction time and dual tasking ability in a simulated driving environment. ISBS Proceedings Archive. 2017;**35**(1):166

[9] Preece MH, Horswill MS, Geffen GM. Driving after concussion: The acute effect of mild traumatic brain injury on drivers' hazard perception. Neuropsychology. 2010;**24**(4):493

[10] Schmidt JD, Hoffman NL, Ranchet M, Miller LS, Tomporowski PD, Akinwuntan AE, et al. Driving after concussion: Is it safe to drive after symptoms resolve? Journal of Neurotrauma. 2017;**34**(8):1571-1578

[11] Schanke A, Rike P, Mølmen A, Østen P. Driving behaviour after brain injury: A follow-up of accident rate and driving patterns 6-9 years post-injury. Journal of Rehabilitation Medicine. 2008;**40**(9):733-736

[12] Rees L, Marshall S, Hartridge C, Mackie D, Weiser M, Erabi G. Cognitive interventions post acquired brain injury. Brain Injury. 2007;**21**(2):161-200

[13] Thompson M, Thompson L, Reid-Chung A. Treating Postconcussion syndrome with LORETA z-score neurofeedback and heart rate variability biofeedback: Neuroanatomical/ neurophysiological rationale, methods, and case examples. Biofeedback. 2015;**43**(1):15-26

[14] Pomeranz B, Macaulay RJ, Caudill MA, Kutz I, Adam D, Gordon D, et al. Assessment of autonomic function in humans by heart rate spectral analysis. American Journal of Physiology: Heart and Circulatory Physiology. 1985;**248**(1):H151-H153

[15] Thompson J, Hagedorn D. Multimodal analysis: New approaches to the concussion conundrum. Journal of Clinical Sport Psychology. 2012;**6**(1):22-46

[16] Gall B, Parkhouse W, Goodman D. Heart rate variability of recently concussed athletes at rest and exercise. Medicine and Science in Sports and Exercise. 2004;**36**:1269-1274

[17] Lehrer PM, Vaschillo E, Vaschillo B, Lu S-E, Eckberg DL, Edelberg R, et al. Heart rate variability biofeedback increases baroreflex gain and peak expiratory flow. Psychosomatic Medicine. 2003;**65**(5):796-805

[18] Francis HM, Fisher A, Rushby JA, McDonald S. Reduced heart rate variability in chronic severe traumatic brain injury: Association with impaired emotional and social functioning, and potential for treatment using biofeedback. Neuropsychological Rehabilitation. 2016;**26**(1):103-125

[19] Hansen AL, Johnsen BH, Thayer JF. Vagal influence on working memory and attention. International Journal of Psychophysiology. 2003;**48**(3):263-274

[20] Kim S, Zemon V, Cavallo MM, Rath JF, McCraty R, Foley FW. Heart rate variability biofeedback, executive functioning and chronic brain injury. Brain Injury. 2013;**27**(2):209-222

[21] Hansen AL, Johnsen BH, Sollers JJ 3rd, Stenvik K, Thayer JF. Heart rate variability and its relation to prefrontal cognitive function: The effects of training and detraining. European Journal of Applied Physiology. 2004;**93**(3):263-272

[22] Lagos L, Thompson J, Vaschillo E. A preliminary study: Heart rate variability biofeedback for treatment of Postconcussion syndrome. Biofeedback. 2013;**41**(3):136-143

[23] Kim S, Rath JF, McCraty R, Zemon V, Cavallo MM, Foley FW. Heart rate variability biofeedback, self-regulation, and severe brain injury. Biofeedback. 2015;**43**(1):6-14

[24] Bhandari T, Thompson L, Reid-Chung A. Treating postconcussion syndrome using neurofeedback: A case study. Biofeedback. 2013;**41**(4):174-182

[25] Shaw L, Zaichkowsky L, Wilson V. Setting the balance: Using biofeedback and neurofeedback with gymnasts. Journal of Clinical Sport Psychology. 2012;**6**(1):47-66

[26] Congedo M, Lubar JF, Joffe D. Low-resolution electromagnetic tomography neurofeedback. IEEE Transactions on Neural Systems and Rehabilitation Engineering. 2004;**12**(4):387-397

[27] Zotev V, Bodurka J. Effects of simultaneous real-time fMRI and EEG neurofeedback in major depressive disorder evaluated with brain electromagnetic tomography. Neuroimage: Clinical. 2020 2020;**28**: 102459

[28] White EK, Groeneveld KM, Tittle RK, Bolhuis NA, Martin RE, Royer TG, et al. Combined neurofeedback and heart rate variability training for individuals with symptoms of anxiety and depression: A retrospective study. NeuroRegulation. 2017;**4**(1):37-55

[29] Bulmash EL, Moller HJ, Kayumov L, Shen J, Wang X, Shapiro CM. Psychomotor disturbance in depression: Assessment using a driving simulator paradigm. Journal of Affective Disorders. 2006;**93**(1-3):213-218

[30] Wong IY, Mahar D, Titchener K. Driven by distraction: Investigating the effects of anxiety on driving performance using the attentional control theory. Journal of Risk Research. 2015;**18**(10):1293-1306

[31] Kaiser DA, Othmer S. Effect of neurofeedback on variables of attention in a large multi-center trial. Journal of Neurotherapy. 2000;**4**(1):5-15

[32] Wigton NL, Krigbaum G. Attention, executive function, behavior, and electrocortical function, significantly improved with 19-channel z-score neurofeedback in a clinical setting: A pilot study. Journal of Attention Disorders. 2019;**23**(4):398-408

[33] Wing K. Effect of neurofeedback on motor recovery of a patient with brain injury: A case study and its implications for stroke rehabilitation. Topics in Stroke Rehabilitation. 2001;**8**(3):45-53

[34] Keizer AW, Verment RS, Hommel B. Enhancing cognitive control through neurofeedback: A role of gamma-band activity in managing episodic retrieval. NeuroImage. 2010;**49**(4):3404-3413

[35] Jasper HH. The ten-twenty electrode system of the international federation. Electroencephalography and Clinical Neurophysiology. 1958;**10**:371-375

[36] King NS, Crawford S, Wenden FJ, Moss NEG, Wade DT. The Rivermead post concussion symptoms questionnaire: A measure of symptoms commonly experienced after head injury and its reliability. Journal of Neurology. 1995;**242**(9):587-592

[37] Spitzer RL, Kroenke K, Williams JB, Lowe B. A brief measure for assessing generalized anxiety disorder: The GAD-7. Archives of Internal Medicine. 2006;**166**(10):1092-1097

[38] Classen S, Bewernitz M, Shechtman O. Driving simulator sickness: An evidence-based review of the literature. American Journal of Occupational Therapy. 2011;**65**(2):179-188

[39] Gianaros PJ, Muth ER, Mordkoff JT, Levine ME, Stern RM. A questionnaire for the assessment of the multiple dimensions of motion sickness. Aviation Space and Environmental Medicine. 2001;**72**(2):115-119

[40] Alvarez L, Classen S, Medhizadah S, Knott M, He W. Pilot efficacy of a DriveFocus intervention on the driving performance of young drivers. Frontiers in Public Health. 2018;**6**:125

[41] Alvarez L, Classen S, Medhizadah S, Knott M, Asantey K, He W, et al. Feasibility of DriveFocus and driving simulation interventions in Young drivers. OTJR: Occupation, Participation and Health. 2018;**38**(4):245-253

[42] Lehrer PM, Vaschillo E, Vaschillo B. Resonant frequency biofeedback training to increase cardiac variability: Rationale and manual for training. Applied Psychophysiology and Biofeedback. 2000;**25**(3):177-191

[43] Eyres S, Carey A, Gilworth G, Neumann V, Tennant A. Construct validity and reliability of the Rivermead post-concussion symptoms questionnaire. Clinical Rehabilitation. 2005;**19**(8):878-887

[44] Nelson DV, Esty ML. Neurotherapy for chronic headache following traumatic brain injury. Military Medical Research. 2015;**2**:22

[45] Surmeli T, Eralp E, Mustafazade I, KosIH, OzerGE, SurmeliOH. Quantitative EEG Neurometric analysis-guided neurofeedback treatment in Postconcussion syndrome (PCS): Forty cases. How is Neurometric analysis important for the treatment of PCS and as a biomarker? Clinical EEG and Neuroscience. 2017;48(3): 217-230.

[46] Bounias M, Laibow RE, Stubblebine AN, Sandground H, Bonaly A. EEG-NeuroBioFeedback treatment of patients with brain injury part 4: Duration of treatments

as a function of both the initial load of clinical symptoms and the rate of rehabilitation. Journal of Neurotherapy. 2002;**6**(1):23-38

[47] Ontario Neurotrauma Foundation. Guidelines for concussion/mild traumatic brain injury & persistent symptoms: for adults (18+ years of age): Ontario Neurotrauma Foundation; 2018.

[48] Ullman JB. Bentler PM. Structural equation modeling. Handbook of Psychology. Second Edition; 2012

[49] Kraft M, Amick MM, Barth JT, French LM, Lew HL. A review of driving simulator parameters relevant to the operation enduring freedom/operation Iraqi freedom veteran population. American Journal of Physical Medicine and Rehabilitation. 2010;**89**(4):336-344

[50] Fergenson PE. The relationship between information processing and driving accident and violation record. Human Factors. 2016;**13**(2):173-176

[51] Bernstein JPK, Calamia M. Assessing the longer-term effects of mild traumatic brain injury on self-reported driving ability. Physical Medicine & Rehabilitation. 2018;**10**(11):1153-1163

[52] Lane AK, Benoit D. Driving, brain injury and assistive technology. NeuroRehabilitation. 2011;**28**(3):221-229

[53] Lindsay S, Stoica A. A systematic review of factors affecting driving and public transportation among youth and young adults with acquired brain injury. Brain Injury. 2017;**31**(10):1257-1269

[54] Lucas JA, Moore JB, Davis S, Brooks JO, Miles C. Provider attitudes and management regarding returning to drive after concussion. British Journal of Sports Medicine. 2018;**53**(8):495

[55] Marshall S, Bayley M, McCullagh S, Velikonja D, Berrigan L, Ouchterlony D, et al. Updated clinical practice guidelines for concussion/mild traumatic brain injury and persistent symptoms. Brain Injury. 2015;**29**(6):688-700

[56] Shekelle PG, Morton SC, Suttorp MJ, Buscemi N, Friesen C. Agency for Healthcare R, et al. challenges in systematic reviews of complementary and alternative medicine topics. Annals of Internal Medicine. 2005;**142**(12 Pt 2):1042-1047

[57] Thomas M, Skilbeck C, Cannan P, Slatyer M. The structure of the Rivermead post-concussion symptoms questionnaire in Australian adults with traumatic brain injury. Brain Impairment. 2017;**19**(2):166-182

[58] Raymond J, Varney C, Parkinson LA, Gruzelier JH. The effects of alpha/theta neurofeedback on personality and mood. Cognitive Brain Research. 2005;**23**(2-3):287-292

[59] Gevensleben H, Holl B, Albrecht B, Vogel C, Schlamp D, Kratz O, et al. Is neurofeedback an efficacious treatment for ADHD? A randomised controlled clinical trial. Journal of Child Psychology and Psychiatry and Allied Disciplines. 2009;**50**(7):780-789