BRAIN. Broad Research in Artificial Intelligence and Neuroscience
e-ISSN: 2067-3957 | p-ISSN: 2068-0473
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2025, Volume 16, Issue 1, pages: 83-94.
Submitted: November 25th, 2024 | *Accepted for publication:* January 11th, 2025

Unveiling the Functional Component in Post-Concussive Cognitive Impairment: A Novel Modelling Approach

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Abstract: *Mild traumatic brain injury (mTBI) is a common public health problem that significantly affects millions of people, especially people in high-risk occupations. Post-concussive cognitive impairment (PCCI) is a prevalent and debilitating outcome of mTBI that has a major impact on cognitive function as well as quality of life, thus affecting long-term health outcomes. Of all traumatic brain injuries, mTBI accounts for 58-88%, according to epidemiological studies. However, mTBI sufferers report a multitude of cognitive and emotional symptoms that constitute post-concussive syndrome (PCS). The most reported symptoms include fatigue, headaches, sensitivity to noise, anxiety, and depression. Although there is progress in understanding biochemical and structural changes after mTBI, memory, attention, and processing speed in PCCI remain poorly understood. This study aims to develop a regression model based on the modified version of Brown's disease cognition model. This model describes both cognitive and behavioural responses as indicators of functional aspects in PCS. In this study, data from 45 patients were analysed to reveal the functional nature of cognitive impairment in PCS, to open the way for more precise interventions. In addition to investigating the physiological aspects of PCS, we aim to recognise the inherent social dimension of the experiences of individuals affected by PCS. Additionally, the often subtle and non-observable nature of symptoms can bring challenges in interpersonal relationships, emphasising the need to enhance awareness among family, colleagues, and employers of the cognitive and behavioural aspects of PCS.*

Keywords: *post-concussive syndrome; functional neurological disorder; cognitive impairment; regression model; behavioural responses; cognitive responses.*

How to cite: Mavroudis, I., Chatzikonstantinou, S., Petridis, F., Kazis, D., Kamal, F. Z.., Diaconu, S., Visternicu, M., Ciobica, A., Iordache, A., Stadoleanu, C., Petroaie, A. D., Novac, B. (2025). Unveiling the functional component in post-concussive cognitive impairment: A novel modeling approach. *BRAIN. Broad Research in Artificial Intelligence and Neuroscience, 16*(1), 83-94. https://doi.org/10.70594/brain/16.1/6

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1. Introduction

Concussion or mild traumatic brain injury is the most common type of traumatic brain injury (McInnes et al., 2017). This public health concern affects a wide spectrum of the population, especially athletes and people engaged in high-risk occupations (pilots, firefighters, military personnel, construction workers, etc.) that require high mental concentration or physical activity (Bjork et al., 2016; LeGoff et al., 2021). Despite the high prevalence of pediatric mTBI, insufficient data are known about its impact on children's social functioning (Lalonde et al., 2018). A significant proportion of people who suffer from concussions experience a set of symptoms known as PCS. This syndrome affects approximately 16% of mTBI patients (Lubbers et al., 2024). It is characterised by physical, emotional, and cognitive symptoms, including headaches, difficulty concentrating, irritability, memory problems, fatigue, difficulty insomnia, dizziness, and depression (Strauss, 1935; Bazarian et al., 1999; Evans, 2010; Ganti et al., 2014). Athletes who develop PCS require individualised care. Among the most common obstacles to assessing the effect of PCS on patient outcomes is the lack of a universal, clinically accepted definition for PCS (Ellis, Leddy, & Willer, 2024).

Although it is widely accepted that PCS symptoms are initially driven by physiological changes in the brain resulting from the injury, a subset of patients continue to experience cognitive symptoms long after the expected healing period (Iverson et al., 2019). The prolonged cognitive impairment in PCS prompts further investigation into its underlying mechanisms and causes. In our previous paper, we proposed the functional overlap model as a possible mechanism that could explain prolonged post-concussion symptoms (Mavroudis et al., 2023). It has been hypothesised that, in some cases, prolonged symptoms may not only be the result of neurological damage but may also have a functional component. Functional neurological disorders (FNDs) involve symptoms not explained by structural brain damage but are believed to result from problems in the functioning of the nervous system (Mavroudis et al., 2023). FND was previously considered a diagnosis of exclusion and is now a diagnosis with treatments available. This disorder generally affects young adults and can cause severe disability in some individuals (Aybek & Perez, 2022).

Drawing inspiration from Brown's cognitive model of unexplained illness, which admits that cognitive and behavioural responses play a role in the perpetuation of symptoms in FND, we aim to adapt and apply this PCS model (Brown & Reuber, 2016, Reuber & Brown, 2017; Mavroudis et al., 2023). It is also hypothesised that cognitive responses, such as catastrophising thoughts about one's condition, and behavioural responses, such as fear-avoidance behaviours, may contribute to the persistence of cognitive impairment in PCS.

In this study, we develop the following regression model:

[Symptom severity = B0 + B1(Cognitive responses) + B2*(Behavioural responses) + e]*

In this regression model, *symptom severity* serves as a proxy for cognitive impairment and is measured using a combination of standardised assessments. *Cognitive responses* and *behavioural responses* are assessed by questionnaires that measure activity levels, attention, thinking, memory, fear-avoidance beliefs, and health anxiety. In practice, *e*, allows the observed values of symptom severity to differ slightly from the values predicted by the regression model. Analysing data from 45 patients, we examine the relationships between cognitive and behavioural responses and symptom severity in PCS. By elucidating potential functional components underlying prolonged cognitive impairment in PCS, this study aims to improve understanding and management strategies for affected individuals.

2. Materials and Methods

2.1. Study Participants

Data were collected from a sample of 45 patients who were diagnosed with PCS. Participants were recruited through online forums and support groups dedicated to brain injury and PCS. In addition, local physicians were approached to refer eligible patients for the study.

Regarding the recruitment process, it should be noted that the eligibility criteria for participants were clearly defined to ensure that only individuals diagnosed with PCS were included.

2.2. Data Collection

Data were collected using a two-pronged approach: online questionnaires and online interviews. Before data collection, all participants were informed about the study's objectives, giving their consent to participate in the study. In order to maintain confidentiality and ensure ethical compliance, all identifiable patient data was fully anonymised.

Online Questionnaires

All participants were asked to complete a series of online questionnaires designed to measure cognitive and behavioural responses and PCS symptom severity. The questionnaires were administered through a secure online platform to maintain confidentiality.

Catastrophic Thinking

Tool: Pain Catastrophising Scale (Quartana, Campbell, & Edwards, 2009).

Description: This self-report questionnaire is designed to measure the extent of catastrophic thinking related to pain. It consists of 13 items and assesses rumination, magnification, and helplessness.

Memory Concerns

Tool: Memory Assessment Clinics Questionnaire (MAC-Q) (Crook, Feher, & Larrabee, 1992).

Description: MAC-Q is a brief questionnaire that assesses age-related changes in memory and helps in identifying individuals with memory impairment. It contains six items that evaluate memory function.

Attention and Concentration

Tool: Test of Variables of Attention (TOVA) (Memória et al., 2018).

Description: TOVA is an objective, neurophysiological measure of attention that is used widely to assess attention-deficit/hyperactivity disorder (ADHD). It evaluates both visual and auditory attention and response inhibition.

Avoidance Behaviour

Tool: Fear Avoidance Beliefs Questionnaire (FABQ) (Panhale, Gurav, & Nahar, 2016).

Description: This self-report measure assesses patients' beliefs about how physical activity and work affect their pain.

Reassurance Seeking Behaviour

Tool: Health Anxiety Inventory (HAI) (Hedman et al., 2015).

Description: It is a self-report measure designed to assess health anxiety. It focuses on the cognitive aspects, behavioural responses, and avoidance patterns associated with health anxiety.

Online Interviews

Online interviews were conducted to gain more in-depth information about patients' experiences, concerns, and perceptions of their condition. These interviews were semi-structured and were conducted by trained interviewers following a standard interview protocol.

PCS Symptom Severity

To assess the severity of post-concussion symptoms, the Rivermead Post-Concussion Symptoms Questionnaire (RPQ) (Crawford, Wenden, & Wade, 1996) was administered. This self-report questionnaire is a simple instrument consisting of 16 items that assess the severity of a range of common post-concussion symptoms. The questions cover the physical, cognitive, and behavioural domains.

2.3. Data Collection and Evaluator Protocol

Data collection was performed by two independent raters who were trained to follow a standardised protocol for administering the RPQ and conducting interviews with participants. The RPQ was administered during an individual interview session with each participant, and all responses were recorded directly into the study database. Any discrepancies between raters regarding symptom severity were resolved through discussion and consensus to ensure the collected data's consistency. This method aims to minimise any potential bias in scoring and increase data reliability.

3. Statistical Analysis

Data from the questionnaires and interviews were compiled and analysed using regression analysis. The regression model was formulated as:

[Symptom Severity = B0 + B1(Cognitive Responses) + B2*(Behavioural Responses) + e]*

According to regression analysis, *Symptom Severity*, measured by the Rivermead Post-Concussion Symptoms Questionnaire, was the dependent variable. *Cognitive Responses* and *Behavioural Responses* were the independent variables (measured by the aforementioned tools); *B0*, *B1*, and *B2* were coefficients, and *e* represented error. For the analysis, we used the Python programming language (Van Rossum & Drake, 2009).

4. Ethical Considerations

This study adhered to ethical standards in the treatment of participants and the handling of data. Informed consent was obtained from all participants, ensuring they were fully informed about the study's purpose, procedures, and potential risks. Data anonymity was maintained throughout the study process, using restricted access to prevent unauthorised disclosure. Furthermore, data was anonymised before analysis, and all efforts were made to protect the participants' identities.

5. Results

5.1. Data Analysis

In this study, seven different variables were analysed: Pain Catastrophising Scale, Memory Assessment Clinics Questionnaire (MAC-Q), Test of Variables of Attention (TOVA), Fear Avoidance Beliefs Questionnaire (FABQ), Health Anxiety Inventory (HAI), Activity Log and Symptom Severity. Each variable was measured on a sample of 45 individuals.

The Pain Catastrophising Scale, the Memory Assessment Clinics Questionnaire (MAC-Q), and the Test of Variables of Attention (TOVA) all showed similar statistical properties (Figure 1). The mean score for these variables was around 21.04 with a standard deviation (SD) of around 5.70. Scores ranged from a low of 7 to a high of 31, with 50% of the midpoint scores (ie, interquartile range) between 18 and 25.

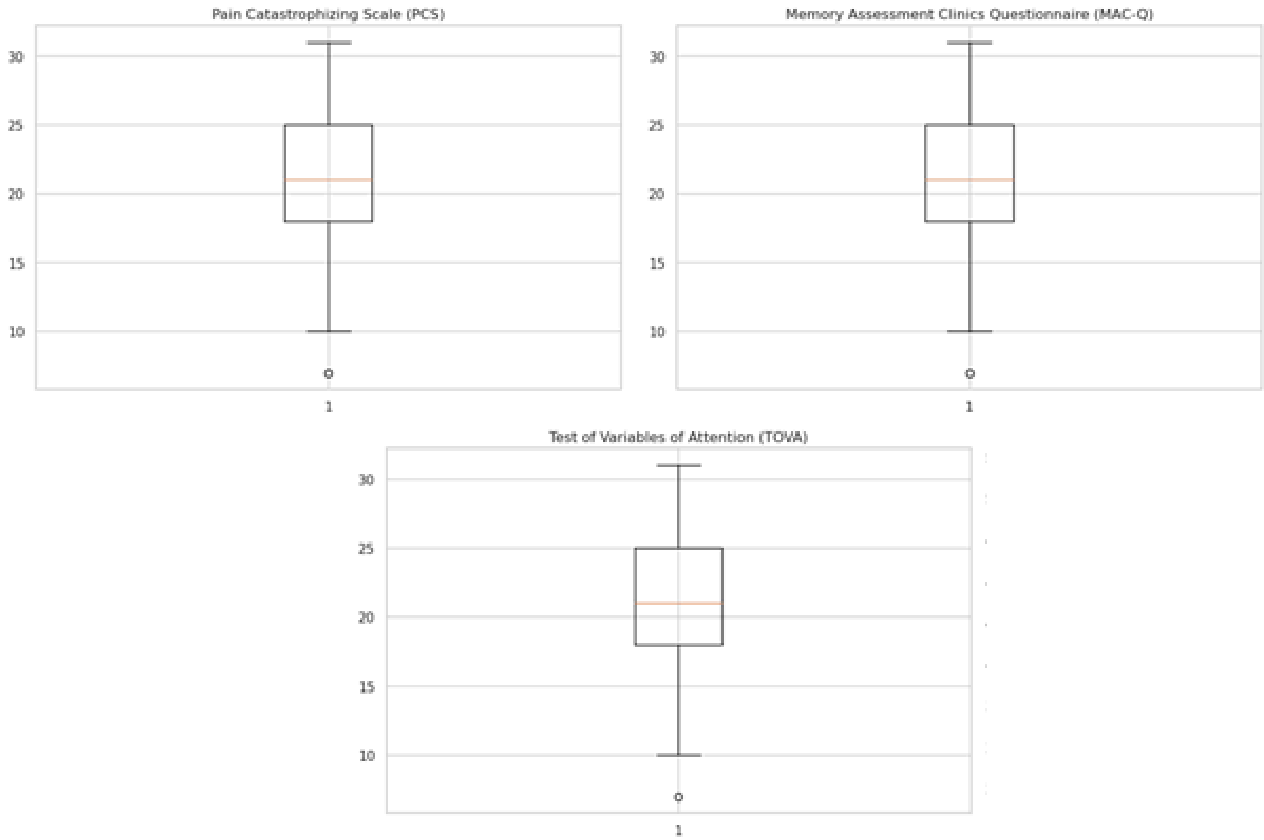

Figure 1. Online questionnaires for assessing cognitive and behavioural responses.

The FABQ and HAI demonstrated comparable statistical characteristics (Figure 2), with a mean score of around 40.09, an SD of around 4.87, and scores ranging from a low of 32 to a high of 52. The interquartile range extended from 36 to 43.

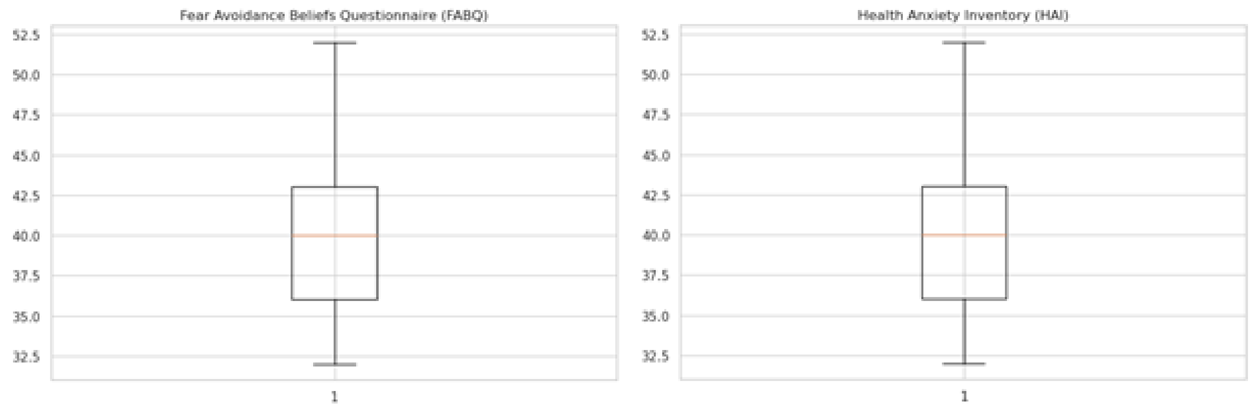

Figure 2. Online quests set for assessing behavioural responses and PCS symptoms severity.

In the study, the Activity Log had an average score of 11.44, with an SD of 1.63 (Figure 3). Scores ranged from 8 to 15, with the middle 50% of the scores (interquartile range) falling between 11 and 13, indicating a relatively concentrated distribution around the mean value. Thus, this measure reflects behaviours related to avoidance or activity limitation, which are associated with the severity of PCS.

Symptom Severity had a mean score of 208.27 and an SD of 11.41. The scores for this variable ranged from 181 to 239, with the interquartile range spanning from 203 to 215, suggesting moderate differences in the perception and response to the concussion, highlighting the heterogeneous nature of PCS.

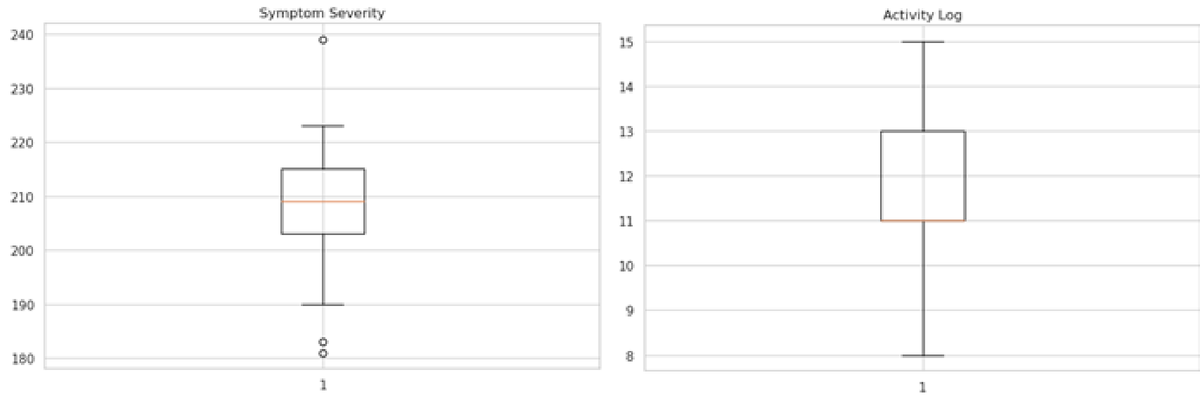

Figure 3. Set of the online quest for evaluating behavioural responses and PCS symptoms severity.

Data were further analysed using a linear regression model to assess the relationship between cognitive and behavioural responses with symptom severity in PCS. The regression model was formulated as follows:

[Symptom Severity = B0 + B1(Cognitive Responses) + B2*(Behavioural Responses) + e]*

5.2. Model Summary

The regression model yielded a statistically significant fit, $F(2, 27) = 15.43$, $p < 0.001$, explaining a substantial proportion of the variance in symptom severity ($R^2 = 0.53$) (Figure 3). This indicates that over half of the variability in symptom severity can be explained by the cognitive and behavioural responses.

5.3. Coefficients

B0 (y-intercept) was found to be 155.19, indicating the severity of baseline symptoms when cognitive and behavioural responses are 0. This represents the reference level for symptom severity in the absence of cognitive and behavioural factors, providing a starting point for further analysis.

B1 (coefficient for cognitive responses) was 0.30, $p < 0.01$, indicating a significant positive relationship between cognitive responses and symptom severity. Specifically, for each unit increase in cognitive responses score (e.g., catastrophic thinking), the severity of symptoms increased by 0.58 units. This means that individuals who report higher levels of catastrophic thinking about their symptoms experience more severe PCS symptoms, supporting the hypothesis that cognitive responses play a significant role in the persistence of symptoms.

B2 (coefficient for behavioural responses) was 0.38, $p < 0.01$, showing a significant positive relationship between behavioural responses and symptom severity. For each unit increase in behavioural responses, symptom severity increased by 0.47 units. This suggests that individuals exhibiting more avoidance behaviours have higher symptom severity, which may contribute to the persistence of PCS symptoms.

5.4. Accuracy of the Model

To further evaluate the model's performance, we used a leave-one-out cross-validation. The average mean squared error was calculated to be 4.17, which indicates that the model has good accuracy in predicting symptom severity (Figure 4).

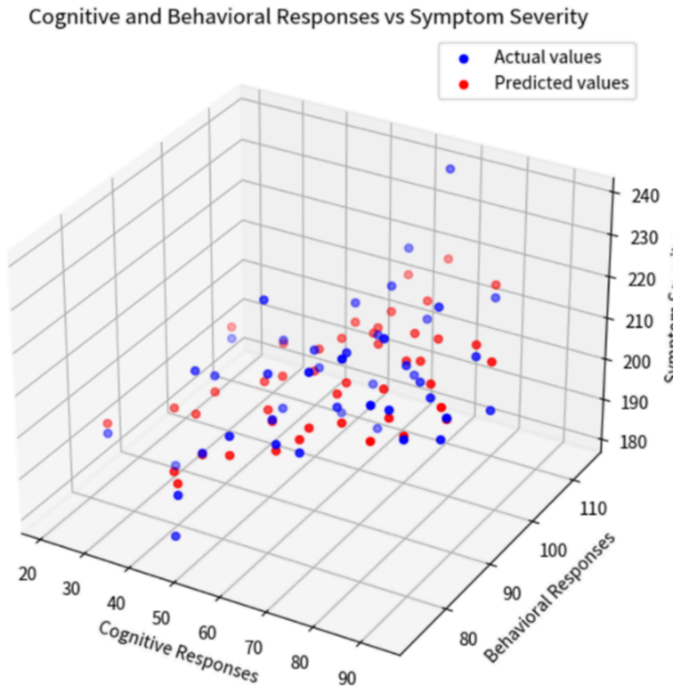

Figure 4. 3-D regression model to assess the relationship between cognitive and behavioural responses and symptom severity in post-concussion.

5.5. Graphical Representation

A scatterplot with a regression line was used to visualise the relationship between cognitive and behavioural responses, but also symptom severity (Figure 5). The graph showed a clear positive trend, supporting the findings from the regression analysis.

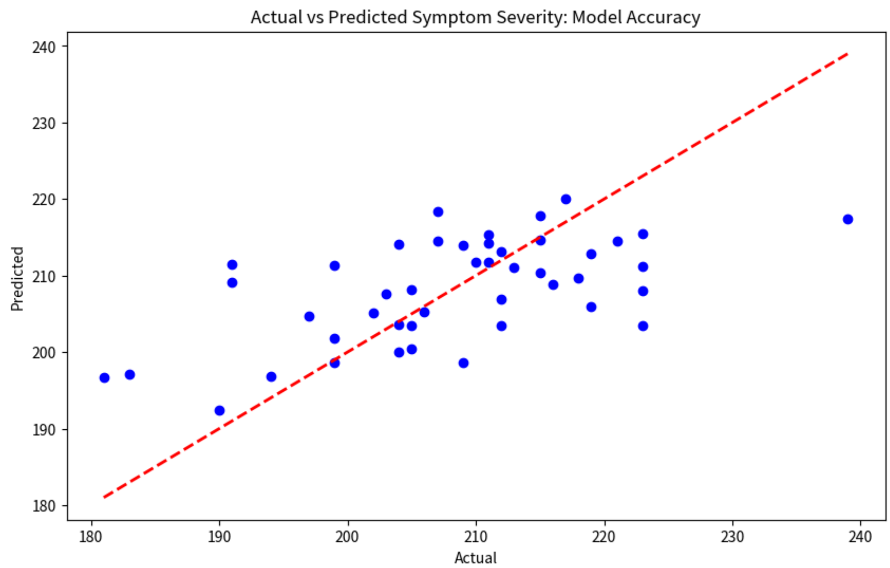

Figure 5. Scatter plot illustrating the relationship between cognitive and behavioural responses and symptom severity.

6. Discussion

The positive coefficients for both B1 and B2 suggest that both cognitive and behavioural factors significantly contribute to the severity of PCS symptoms. These findings align with the hypothesis that maladaptive cognitive patterns (e.g., catastrophic thinking) and avoidance behaviours are important predictors of PCS severity. This not only highlights the complex interplay between psychological and behavioural factors in the persistence and exacerbation of symptoms post-concussion but also emphasises the need for a multifaceted approach in clinical practice. The results support that the regression model can significantly predict symptom severity based on cognitive and behavioural responses in patients with FND. Considering the frequency, consequences, and prognosis, this tumor has been called a "crisis for neurology" (Voon et al., 2016). The model indicates a strong relationship, accounting for more than 50% of the variability in symptom severity. All of this suggests that cognitive and behavioural responses are important factors in predicting and understanding symptom severity in PCS. Both cognitive responses, including memory concerns and catastrophic thinking, and behavioural responses, such as avoidance and reassurance-seeking behaviour, showed a positive relationship with symptom severity. This correlation suggests that interventions targeting these maladaptive cognitive and behavioural responses could be crucial in managing and alleviating the severity of PCS symptoms.

All these results provide support for the functional element in post-concussive cognitive impairment. It is imperative that clinicians consider cognitive and behavioural aspects when managing and evaluating patients with PCS, as addressing these responses could have a significant impact on alleviating symptom severity.

Furthermore, the parallels observed between FND and PCS in terms of cognitive and behavioural responses, as previously discussed in studies (Mavroudis et al., 2023), provide additional support for the relevance of a functional approach in managing PCS. The use of cognitive-behavioural techniques, like those used in FND, could be beneficial in treating, helping clinicians in addressing both cognitive and behavioural aspects to improve patient outcomes. This approach could facilitate not only symptom reduction but also functional recovery by directly targeting the dysfunctional patterns observed in post-concussive syndrome patients. Thus, clinicians must integrate a comprehensive assessment of behavioural and cognitive factors when managing post-concussive syndrome. In addition to assessing symptom severity, this should also involve recognising the role of psychological responses in the persistence of symptoms. Future research should explore longitudinal interventions that combine cognitive-behavioural therapies with tailored strategies to mitigate maladaptive responses, thereby improving clinical outcomes for patients with post-concussive syndrome.

6.1. Cognitive Responses

Among the cognitive responses that were analysed was catastrophic thinking, which reflects exaggerated negative beliefs about the consequences of symptoms or pain. Consistent with previous research on FND (Seto & Nakao, 2017), our findings suggest that individuals with post-concussive syndrome also exhibit catastrophic thinking, which is positively associated with symptom severity. This alignment reinforces the hypothesis that maladaptive cognitive responses may underlie the perception of symptom severity in both conditions. These results may suggest that patients exhibiting higher levels of catastrophic thinking may perceive their symptoms as more severe and debilitating, highlighting the need for targeted cognitive intervention.

Memory concerns also emerged as a prominent cognitive response in PCS patients. PCS patients often report subjective memory impairment (Stillman et al., 2020). This is about previous literature linking cognitive impairment in PCS with aspects of NDF, where patients often have concerns about memory loss or cognitive decline without clear organic causes (Mavroudis et al., 2023). These parallels further support the notion of shared cognitive mechanisms between PCS and FND, underscoring the importance of addressing these concerns in clinical management.

6.2. Behavioural Responses

Behavioural responses, such as avoidance behaviour and reassurance seeking, were also correlated with symptom severity. Avoidance behaviour is characterised by patients avoiding activities that they believe may exacerbate symptoms while reassurance-seeking behaviour includes repeatedly consulting health care providers to obtain confirmation that nothing is seriously wrong.

This is seen in FND and mirrors what is seen in PCS, as individuals may avoid physical and cognitive activities for fear of worsening symptoms or seek repeated medical consultations for reassurance (Holtman et al., 2021).

6.3. Interlink with Brown's Cognitive Model

Our findings also correlate with the key aspects of Brown's cognitive model of unexplained illness (Brown & Reuber, 2016; Reuber & Brown, 2017), which posits that illness perceptions, catastrophic thinking, and behaviours such as avoidance, contribute to the maintenance of unexplained symptoms. Our study extends this model to PCS by empirically demonstrating similar cognitive and behavioural patterns in PCS patients.

6.4. Clinical Implications

Considering the similarities in cognitive and behavioural responses between FND and PCS, adopting a whole patient care approach could be beneficial. Previous research shows promising results when a comprehensive approach used in FND is applied to PCS (Mavroudis et al., 2023). However, clinicians should be alert to the functional aspects of PCS, as addressing cognitive and behavioural responses may play a crucial role in the management and alleviation of symptoms. It is also essential that people with PCS and FND have a work environment that understands their limitations and provides necessary accommodations (flexible work schedule, responsibilities adapted to cognitive difficulties, changes in the workspace to reduce noise exposure or bright lights, extra breaks or the option to work from home) (Beaton, Hadly, & Babul, 2021; Karmali, Beaton, & Babul, 2022, Sharma; 2022).

6.5. Impact on work

People suffering from FND and/or PCS may encounter tasks that can affect their mental health which can lead to decreased performance at work. For patients with FND, sensitivity to noise and light can also be challenging in normal office environments. Furthermore, a supportive work environment is recommended for people experiencing PCS and FND. These aspects involve a deeper understanding of the limitations of these individuals and help implement essential accommodations for each. These include adjusting responsibilities to accommodate cognitive difficulties, offering a quiet workspace with low lighting, offering flexible working hours by allowing extra breaks or even exploring the option of telecommuting. As people with FND begin to let go of their struggle with unnecessary fears and thoughts, both physical and occupational therapy can play a critical role in regaining lost function. Understanding that the recovery period can be variable could be beneficial to both the employee and the employer (Beaton, Hadly, & Babul, 2021; Karmali, Beaton, & Babul, 2022; Sharma, 2022).

6.6. Limitations and Future Research

The present study’s relatively small sample size (45 patients) requires cautious interpretation of the results. For more robust validation, future studies involving larger sample sizes and diverse populations. This would enhance the understanding of how cognitive and behavioural responses vary across different demographic and clinical backgrounds.

Furthermore, longitudinal studies could provide insights into the causal relationships between cognitive and behavioural responses and symptom severity in PCS. However, the data provided in this study are limited in their ability to track this relationship over time due to the short duration of observation. Future research should focus on longer-term assessment, not only of symptomatology such as headache but also of variable emotional and cognitive changes that may occur over time (LeGoff et al., 2021; Sharma, 2022). This approach would allow a deeper understanding of the progression and stability of cognitive impairment in PCS and the factors contributing to its persistence.

7. Conclusions

This study substantiates the functional component underlying cognitive impairment in post-concussion. The observed similarities between cognitive and behavioural responses in post-concussion syndrome and functional neurological disorder underscore a significant association with symptom severity. These results emphasise the necessity of addressing both cognitive and behavioural aspects to enhance the effectiveness of PCS management. Our findings highlight the need for integrated therapeutic approaches that address both cognitive and behavioural dysfunctions in PCS. Building on the similarities with FND, this study opens avenues for refining management strategies, potentially improving patient outcomes through personalised interventions.

Declaration of Conflicting Interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and publication of this article.

Data Availability Statement

All data used is available on request.

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