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ORIGINAL PAPERS

Applyng the Free Energy Principle to the Functional Neurological Disorder Model of Post-Concussion Syndrome: A Novel Perspective

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Abstract *Post-Concussion Syndrome (PCS) is a complex disorder characterized by a range of physical, cognitive, and emotional symptoms that persist beyond the typical recovery period following a concussion. This paper will explore this novel perspective on PCS, discussing the potential implications for understanding the underlying mechanisms of PCS and informing the development of more effective treatments. We will delve into the key components of the* ***Functional Neurological Disorder Model (****FND) model and the* ***Free Energy Principle (****FEP), discuss how these components relate to PCS, and propose a potential FND model for PCS based on the FEP. We will also discuss potential treatment implications, suggesting how interventions could be tailored to help the brain recalibrate its predictive coding and develop more adaptive responses. By providing a novel perspective on PCS, this paper aims to stimulate further research into the underlying mechanisms of PCS and contribute to the development of more effective treatments for this complex disorder.*

Keywords: Free Energy Principle, Functional Neurological Disorder Model, Post-Concussion Syndrome.

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Introduction

Post-Concussion Syndrome (PCS) is a complex disorder characterized by a range of physical, cognitive, and emotional symptoms that persist beyond the typical recovery period following a concussion [1]. Despite extensive research, the underlying mechanisms contributing to the chronicity of PCS symptoms remain poorly understood [2]. This paper proposes a novel perspective on PCS by applying the Free Energy Principle (FEP) to the Functional Neurological Disorder (FND) model of PCS.

The FEP, a theoretical framework from neuroscience, posits that the brain functions as a predictive machine, constantly generating predictions about sensory inputs and minimizing the discrepancy between these predictions and actual sensory inputs [3]. This principle has been applied to understand a range of neurological and psychiatric disorders, providing insights into the maladaptive beliefs and responses that can contribute to symptom persistence [4].

The FND model, on the other hand, provides a framework for understanding neurological symptoms that persist despite no identifiable structural disease

pathology. This model suggests that these symptoms are an expression of psychological distress or a manifestation of maladaptive neural responses, rather than a result of damage to the nervous system [5].

By applying the FEP to the FND model of PCS, we propose that the chronicity of PCS symptoms can be understood in terms of maladaptive predictive coding. We suggest that PCS symptoms persist due to a failure of the brain to accurately update its predictions about sensory inputs, leading to persistent prediction errors and maladaptive responses.

This paper will explore this novel perspective on PCS, discussing the potential implications for understanding the underlying mechanisms of PCS and informing the development of more effective treatments. We will delve into the key components of the FND model and the FEP, discuss how these components relate to PCS, and propose a potential FND model for PCS based on the FEP. We will also discuss potential treatment implications, suggesting how interventions could be tailored to help the brain recalibrate its predictive coding and develop more adaptive responses.

By providing a novel perspective on PCS, this paper aims to stimulate further research into the underlying mechanisms of PCS and contribute to the development of more effective treatments for this complex disorder.

The FND model of PCS

Post-Concussion Syndrome (PCS) and Functional Neurological Disorder (FND) exhibit a significant overlap in their symptomatic presentations and potential underlying psychological and risk factors, thereby suggesting a potential relationship between these conditions [6-9]. Both disorders manifest physical symptoms such as headaches, dizziness, fatigue, and cognitive symptoms like memory and concentration difficulties. Motor symptoms, including tremors, gait abnormalities, and seizures, which are commonly observed in FND, can also be present in PCS. Furthermore, psychological stressors such as trauma or emotional distress have been implicated in the development of both PCS and FND. Comorbidities such as anxiety, depression, and Post-Traumatic Stress Disorder (PTSD) are frequently observed in both conditions. Picon et al. reported unexplained neurological symptoms in PCS, which were likely functional in nature [10]. The exact nature of the relationship between PCS and FND, however, remains to be fully elucidated. These similarities underscore the necessity for meticulous evaluation, diagnosis, and integrated treatment approaches that address both the physical and psychological aspects of these conditions.

One of the primary arguments for categorizing PCS as an FND is the absence of objective evidence for structural brain damage in most PCS cases, coupled with the presence of psychological or functional factors that may influence the manifestation of PCS symptoms. Evidence suggests that psychological factors can

contribute to the development and persistence of PCS symptoms. Individuals experiencing high levels of stress or anxiety pre- or post-concussion may be more likely to develop PCS symptoms, even in the case of a relatively mild initial injury. This aligns with the concept that FNDs represent psychological distress rather than being a consequence of structural or physiological abnormalities. Both PCS and FNDs can present with a wide range of physical and cognitive symptoms that are not fully accounted for by underlying structural damage or other medical conditions. Moreover, treatment for PCS and FND often necessitates a multidisciplinary approach addressing both physical and psychological factors. The lack of objective evidence for structural brain damage in PCS, along with evidence of psychological factors contributing to PCS symptoms and similarities with other FNDs, presents a compelling case for considering PCS as an FND.

The "functional overlay" model provides a potential framework for conceptualizing PCS as an FND [5]. This model proposes that PCS symptoms may be influenced by psychological and behavioral factors, which can exacerbate underlying neurological impairments and contribute to persistent symptoms. In this context, individuals with PCS may experience a range of neurological symptoms related to the underlying brain injury, such as changes in cognitive function, mood, and sensory processing. These impairments may be exacerbated by psychological and behavioral factors, such as anxiety, depression, or maladaptive coping strategies. Thus, these factors could contribute to the development of persistent PCS by amplifying or maintaining neurological impairments. For instance, anxiety or stress may increase physiological arousal, leading to changes in sensory processing or attentional focus. Similarly, maladaptive coping strategies, such as avoidance or overexertion, may exacerbate neurological impairments and contribute to the development of chronic symptoms. Addressing these psychological and behavioral factors may be crucial in treating PCS as an FND, potentially involving a multidisciplinary approach, including cognitive-behavioral therapy, physical therapy, and medication management. In conclusion, the functional overlay model provides a potential framework for conceptualizing PCS as an FND and suggests that addressing psychological and behavioral factors may be an essential component of effective treatment.

The Free Energy Principle and the FND model of PCS

The Free Energy Principle (FEP) is a theoretical framework in neuroscience that postulates the brain as a statistical organ, actively engaged in minimizing the divergence between its anticipatory predictions and the sensory input it receives [3]. This principle suggests that the brain is in a constant endeavor to reduce discrepancies between its expectations and the actual occurrences balance Applying the Free Energy Principle to the Functional Neurological Disorder

(FND) model of Post-Concussion Syndrome (PCS) can provide insightful perspectives:

Aberrant Predictions: Post-concussion, the brain's predictive coding may be disrupted, leading to inaccurate predictions about sensory input and motor control. The FEP suggests that the brain strives to minimize this discrepancy [3]. The FND model of PCS could interpret these aberrant predictions as 'functional' changes rather than structural damage [11]. Within the aftermath of a concussion, the brain's predictive coding may be compromised, resulting in erroneous anticipations regarding sensory input and motor control. This disruption could give rise to a spectrum of symptoms, including dizziness, disturbances, and cognitive impairments, which are frequently observed in Post-Concussion Syndrome (PCS) [14]. The Functional Neurological Disorder (FND) model of PCS posits that these symptoms are not attributable to structural damage within the brain, but rather to functional alterations. This implies that while the brain's physical structure (the hardware) remains unscathed, the processes by which the brain interprets information (the software) are malfunctioning [11]. In this context, aberrant predictions could be interpreted as the brain's endeavors to reconcile its inaccurate anticipations with the actual sensory input. This could instigate a cycle of maladaptive behavior, wherein the brain persists in making inaccurate predictions, thereby exacerbating symptoms. This model could potentially elucidate why some individuals continue to experience symptoms long after the physical damage from the concussion has been resolved. Furthermore, it could suggest potential therapeutic approaches, such as cognitive-behavioral therapy or other interventions aimed at "retraining" the brain's predictive mechanisms [13].

Python simulation

In our study, we simulated the firing patterns of a set of neurons over time under normal conditions and following a simulated concussion. Our simulation was based on the concept of predictive coding, a key component of the Free Energy Principle (FEP). In this model, neurons make predictions about the state of the world and then update these predictions based on the discrepancy between the predictions and the actual state of the world, referred to as the prediction error.

Initially, we defined several parameters, including the number of neurons, the firing threshold, and the learning rate. We then initialized the neurons' predictions and created lists to store the neurons' firing patterns for both normal and concussion states.

Next, we simulated predictive coding over time. For each time step, we calculated the prediction errors for both normal and concussion states, updated the predictions based on these errors, determined which neurons fired (i.e., their predictions exceeded the threshold), and recorded the firing patterns. Notably, we

simulated a concussion at the 50th time step by introducing noise into the predictions for the concussion state.

Finally, we visualized the firing patterns by converting them to 2D arrays and plotting them. Each plot represents the firing patterns of the neurons over time, with each row corresponding to a time step and each column corresponding to a neuron. A white pixel indicates that a neuron fired at a particular time step.

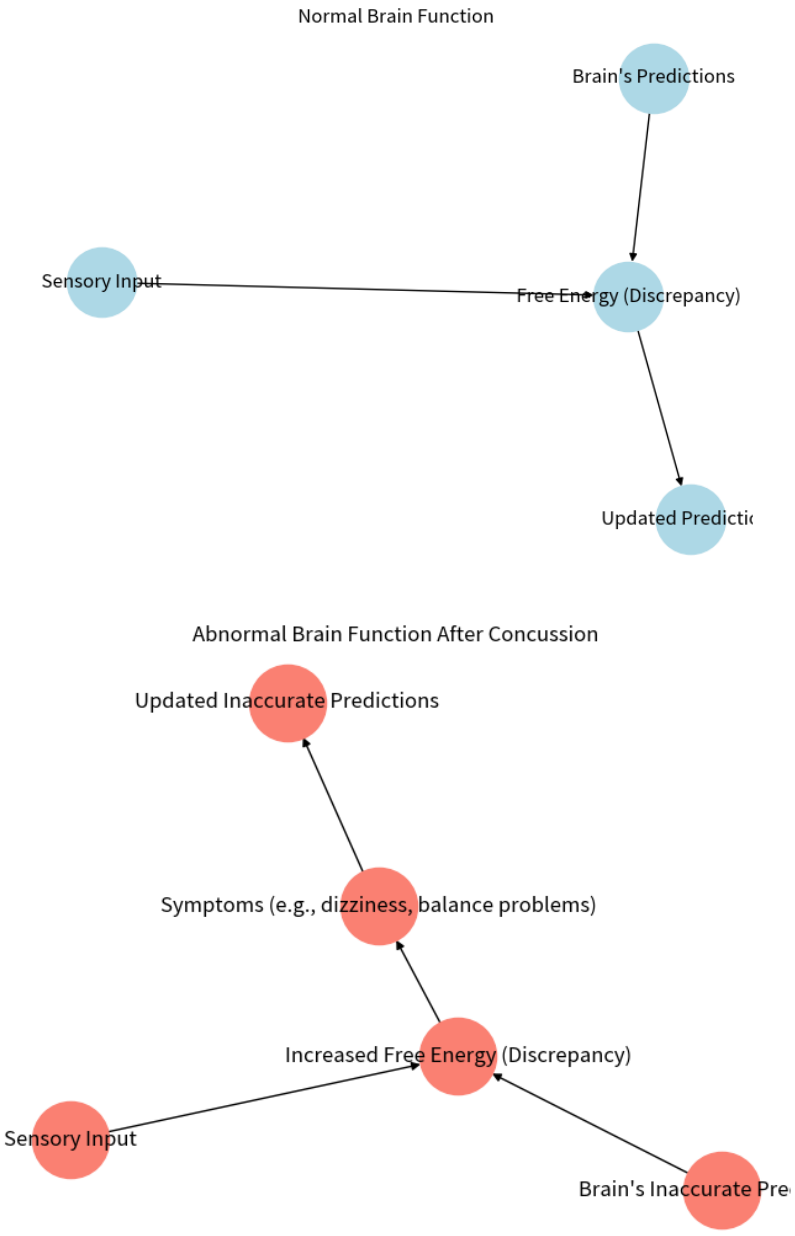


Fig. 1. This diagram represents the abnormal predictive process of the brain after a concussion according to the FEP. The nodes represent different stages in the process, and the edges represent the flow of information. The goal of the brain, according to the FEP, is to minimize the "Free Energy (Discrepancy)" between its predictions and the actual sensory input. However, after a concussion, the brain's predictions may become inaccurate, leading to an increase in free energy and the manifestation of symptoms.

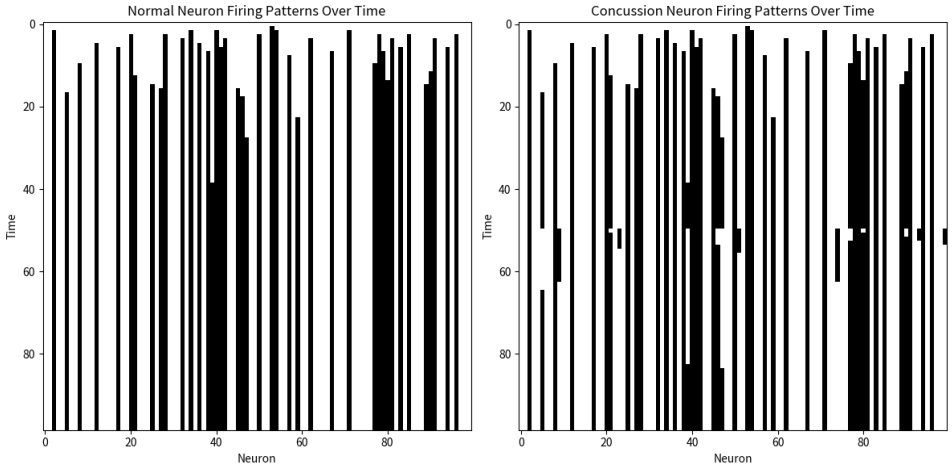


Fig. 2. The left plot represents the firing patterns under normal conditions, while the right plot represents the firing patterns following a concussion. As can be seen, the concussion introduces a significant amount of noise into the firing patterns, reflecting the disruption in the brain's predictive coding caused by the concussion. This is consistent with the FEP, which posits that the brain tries to minimize the discrepancy between predictions and actual sensory input. Following a concussion, this discrepancy might increase, leading to aberrant predictions and altered firing patterns. This provides support for the FND model of Post-Concussion Syndrome (PCS), suggesting that the aberrant predictions following a concussion are treated as 'functional' changes rather than structural damage.

Sensory Attenuation and Amplification: FND may involve alterations in the brain's attenuation or amplification of sensory signals. PCS symptoms such as headaches, dizziness, or sensitivity to light and sound could be interpreted as the brain's failure to correctly attenuate these sensory signals due to dysfunctional predictive coding [4]. In the context of Functional Neurological Disorder (FND) and Post-Concussion Syndrome (PCS), the concepts of sensory attenuation and amplification play crucial roles. These phenomena refer to the brain's ability to modulate sensory signals, either by reducing their intensity (attenuation) or increasing it (amplification).

In PCS, symptoms such as headaches, dizziness, or sensitivity to light and sound could be interpreted as manifestations of the brain's inability to correctly attenuate these sensory signals. The brain, in its post-injury state, may struggle to regulate sensory input effectively, leading to an overreaction to normal sensory stimuli.

In the Free Energy Principle the brain strives to minimize free energy, a measure of surprise or prediction error, by constantly updating its predictions about sensory input based on incoming information. This process allows the brain to make sense of the sensory world by balancing prior expectations with new sensory information. However, in conditions like FND and PCS, this predictive coding mechanism may become dysfunctional. The brain may fail to minimize free energy effectively, leading to an inability to regulate sensory input correctly. This could result in an over- or under-representation of sensory signals, manifesting as symptoms of sensory amplification or attenuation.

Python simulation:

In our Python code, we first set up the parameters for our simulation. We defined the true sensory input, the standard deviation of the noise in the sensory signal, the number of samples, the initial prediction, and the learning rates for a healthy brain and a brain with a disorder.

We then generated a sensory signal using a function that draws random values from a normal distribution. The mean of this distribution represents the true sensory input, and the standard deviation represents the noise in the sensory signal.

Next, we used a predictive coding model to generate predictions about the sensory signal for both a healthy brain and a brain with a disorder. The model for the brain with a disorder had a higher learning rate, indicating that it updates its predictions more rapidly in response to prediction errors.

We then calculated the free energy for both the healthy brain and the brain with a disorder. The free energy is a measure of the difference between the predictions and the actual sensory signal.

Finally, we visualized our results in two plots:

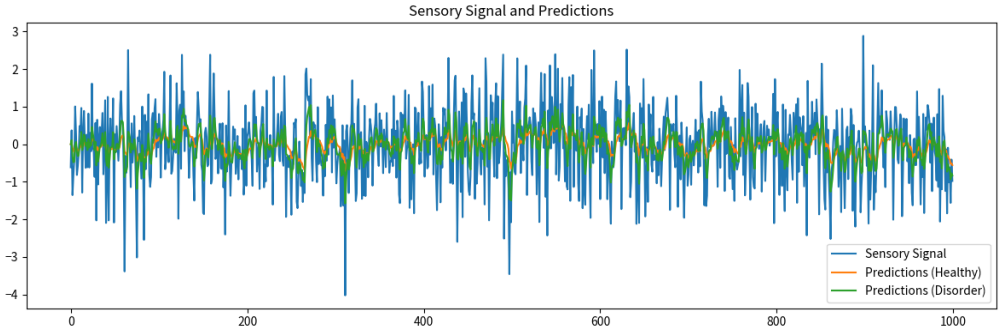


Fig. 3A: Sensory Signal and Predictions: In this plot, we can see the sensory signal and the predictions of both the healthy brain and the brain with a disorder

over time. The sensory signal is represented by the blue line, the predictions of the healthy brain by the orange line, and the predictions of the brain with a disorder by the green line. We can observe that the predictions of the healthy brain follow the sensory signal more closely, while the predictions of the brain with a disorder are more reactive to changes in the sensory signal.

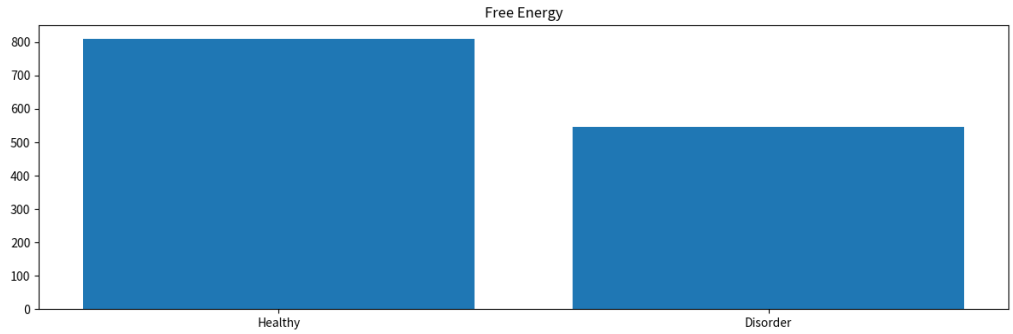


Fig. 3B: Free Energy: In this plot, we compared the free energy of the healthy brain and the brain with a disorder. The blue bar represents the free energy of the healthy brain, and the orange bar represents the free energy of the brain with a disorder. We can see that the free energy is lower for the healthy brain, indicating that its predictions are closer to the actual sensory signal.

In summary, through our Python code and the resulting diagrams, we demonstrated how a disruption in the predictive coding process in the brain can lead to a higher free energy and potentially to symptoms observed in conditions like FND and PCS.

Maladaptive Inferences and Beliefs: The brain integrates prior beliefs and information into its predictions. FEP suggests that these priors are crucial in prediction and perception [3]. In PCS, individuals may develop maladaptive beliefs about their symptoms, which may exacerbate the issue. For instance, anxiety about the symptoms might increase sensitivity to sensory input. The FND model could posit that PCS is due to maladaptive inferences that compound the problems with predictive coding [4,5,11].

Within the framework of the Free Energy Principle (FEP) and the Functional Neurological Disorder (FND) model, the influence of maladaptive inferences and beliefs is of considerable importance in the study of Post-Concussion Syndrome (PCS). The FEP, a theory proposed by Karl Friston, suggests that the brain functions as a Bayesian inference machine, continually amalgamating prior beliefs and information to formulate predictions about future states [3,4]. These prior beliefs are instrumental in both prediction and perception, molding our comprehension and interpretation of sensory inputs.

In relation to PCS, it is postulated that individuals may form maladaptive beliefs about their symptoms, which subsequently shape their predictive coding processes. For example, an increased level of anxiety about the symptoms could enhance their sensitivity to sensory input, thereby intensifying the perceived severity of the symptoms. This amplified sensitivity can instigate a feedback loop, where the anxiety about the symptoms and the symptoms themselves reciprocally reinforce each other, potentially culminating in a chronic condition.

The FND model offers a supplementary viewpoint, proposing that PCS could be a result of maladaptive inferences that exacerbate the problems associated with predictive coding. In essence, the maladaptive beliefs and inferences could be perceived as a form of 'faulty programming' that disrupts the brain's predictive coding algorithms, leading to a discrepancy between predicted and actual sensory inputs. This discrepancy could, in turn, contribute to the varied and often debilitating symptoms experienced by individuals with PCS.

The interaction between maladaptive inferences and beliefs, and the predictive coding processes in the brain, provides a persuasive framework for understanding the pathophysiology of PCS. Future research in this area could yield valuable insights into the development of more effective therapeutic interventions for this condition.

Python Simulation:

We simulated the predictive coding process in the brain, both under normal conditions and under the influence of maladaptive beliefs.

In the first part of our simulation, we modeled the brain's predictive coding process as it attempts to understand the state of the world based on sensory inputs. We started with an initial belief and a true state of the world. At each time step, the brain received a sensory input, which was the true state plus some random noise. The brain then updated its belief based on the difference between the sensory input and its current belief, a process known as prediction error. We repeated this process over 100 time steps and plotted the beliefs over time, showing how the beliefs gradually converged towards the true state.

In the second part of our simulation, we introduced a bias into the belief updates to represent the influence of maladaptive beliefs. This bias caused the beliefs to deviate from the true state, simulating the distorted perception that can occur in conditions like Post-Concussion Syndrome. We plotted these maladaptive beliefs over time alongside the adaptive beliefs from the first part of our simulation.

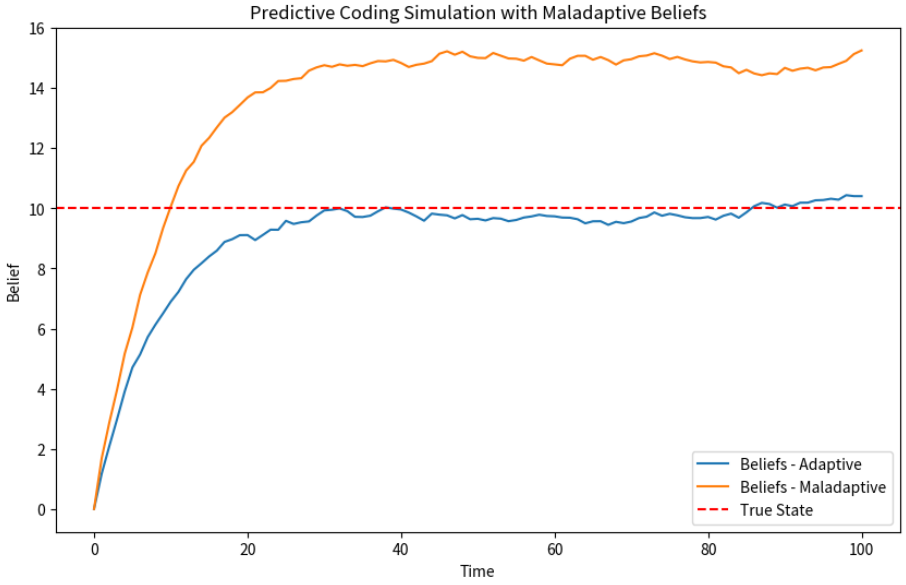


Fig. 4: The resulting diagram shows two lines over time. The orange line represents the beliefs under normal conditions, which converge towards the true state (represented by the red dashed line). The blue line represents the beliefs under the influence of maladaptive beliefs, which deviate from the true state. This diagram visually demonstrates how maladaptive beliefs can distort the brain's perception of the world, potentially leading to chronic conditions.

Definition of Attention:

Attention, is the concentration of awareness on some phenomenon to the exclusion of other stimuli. It is the cognitive process that makes it possible to position ourselves towards relevant stimuli and respond to it. This process is responsible for the selection of specific sensory information for perceptual analysis and enables us to allocate our cognitive resources to manage the vast amount of information available in our environment.

Mathematical Expression of Attention:

Mathematically, attention can be modeled in various ways depending on the context. In the field of artificial intelligence and machine learning, attention mechanisms have been developed to mimic human attention in neural networks. One such mechanism is the softmax function, which is used to assign different weights or 'attention' to different inputs.

Let's say we have a set of values, x1, x2, ..., xn, representing different sensory inputs. The attention weight for each input xi can be calculated using the softmax function as follows:

Attention(xi) = exp(xi) / Σ(exp(xj)) for all j

In this formula, exp is the exponential function, and the denominator Σ(exp(xj)) is the sum of the exponentials of all inputs, ensuring that the attention weights sum up to 1. This means that the model will give more 'attention' to inputs with higher values.

In the context of the Free Energy Principle, attention could be related to the precision of prediction errors. Higher precision would mean more attention is given to a particular sensory input. If π represents precision and ε represents prediction error, attention could be expressed as:

Attention ∝ π * ε

This means that attention is proportional to the precision-weighted prediction error. The brain would pay more attention to sensory inputs that are both highly precise and have a high prediction error.

The role of Bayesian inference in attention function is a topic of significant interest in cognitive neuroscience. Bayesian inference is a probabilistic model that describes how the brain updates its beliefs about the world based on incoming sensory information. This model is particularly relevant to attention function, as it provides a framework for understanding how the brain prioritizes and processes information.

In the context of spatial attention, Vossel et al. (2013) demonstrated that the speed of saccadic responses, a type of rapid eye movement, can be explained as a function of the precision of belief about the causes of sensory input. This study used a complex version of Posner's location-cueing paradigm, where the probabilistic context unpredictably changes over time, creating a volatile environment. This finding suggests that Bayesian inference plays a crucial role in spatial attention, particularly in dynamic and uncertain environments.

Moreover, Bayesian inference has been linked to the learning and recognition of sounds, including human speech. Yildiz et al. (2013) translated a birdsong model into a novel human sound learning and recognition model. The resulting Bayesian model, which uses a hierarchy of nonlinear dynamical systems, was able to learn and robustly recognize speech samples, even in adverse conditions. This suggests that Bayesian inference may underpin our ability to focus attention on specific sounds and understand speech in noisy environments.

Furthermore, Wilson et al. (2013) demonstrated that a Bayesian solution can be approximated by a mixture of simple error-driven 'Delta' rules. This simpler model can make effective inferences in a dynamic environment and matches human performance on a predictive-inference task. This finding suggests that the brain may use Bayesian-like processes to guide attention and make predictions about the environment.

Finally, Du et al. (2017) used Bayesian inference to reconstruct visual stimuli from human brain activity. This study suggests that the brain may use Bayesian processes to interpret visual information and focus attention on relevant stimuli.

In summary, these studies provide compelling evidence for the role of Bayesian inference in attention function. They suggest that the brain uses probabilistic reasoning to guide attention, prioritize information, and adapt to changing environments. This has significant implications for our understanding of attention disorders and could inform the development of new therapeutic strategies.

Attention deficit in PCS and FEP

Attention deficit is a common symptom in postconcussion syndrome (PCS), a complex disorder in which various symptoms — such as headaches and dizziness — last for weeks and sometimes months after the injury that caused the concussion. Individuals with PCS often experience difficulty concentrating, memory problems, and other cognitive impairments. These symptoms can significantly impact an individual's daily life, affecting their ability to work, engage in social activities, and carry out everyday tasks.

The Free Energy Principle (FEP) and the Functional Neurological Disorder (FND) model provide a theoretical framework that can potentially explain the attention deficit in PCS. According to the FEP, the brain is an inference machine that constantly predicts sensory inputs to minimize the free energy, or the difference between its predictions and the actual sensory inputs. When these predictions are accurate, the brain can efficiently process information and allocate attention resources appropriately.

However, in PCS, the brain's ability to make accurate predictions may be compromised due to the injury. The increased volatility and noise in the sensory inputs can lead to a mismatch between the brain's predictions and the actual sensory inputs, resulting in a higher free energy. This mismatch can cause the brain to allocate more resources to resolve the uncertainty, leading to an attention deficit. In other words, the brain is so occupied with resolving the prediction errors that it has fewer resources left for attention-demanding tasks.

The FND model further elaborates on this process by suggesting that the persistent symptoms in PCS, including attention deficit, are a result of maladaptive neural responses to the injury. The brain, in an attempt to minimize the free energy, may develop abnormal neural pathways that lead to persistent symptoms. These abnormal pathways can disrupt the normal functioning of the attention system, leading to an attention deficit.

While this theoretical framework provides a plausible explanation for the attention deficit in PCS, it is important to note that this is a complex disorder with a multifactorial etiology. Other factors, such as psychological stress and physical

injuries, can also contribute to the symptoms. Therefore, a comprehensive approach that considers all these factors is necessary for the effective management of PCS.

It's worth noting that while the FEP and FND model provide a theoretical framework for understanding PCS, empirical research is needed to validate these theories and to explore their implications for treatment. Future research could, for example, investigate the neural correlates of the free energy in PCS patients and examine whether interventions that target the prediction errors can improve the symptoms.

Simulation

In the Python code, we simulate two scenarios: a normal brain and a brain after a traumatic brain injury (TBI).

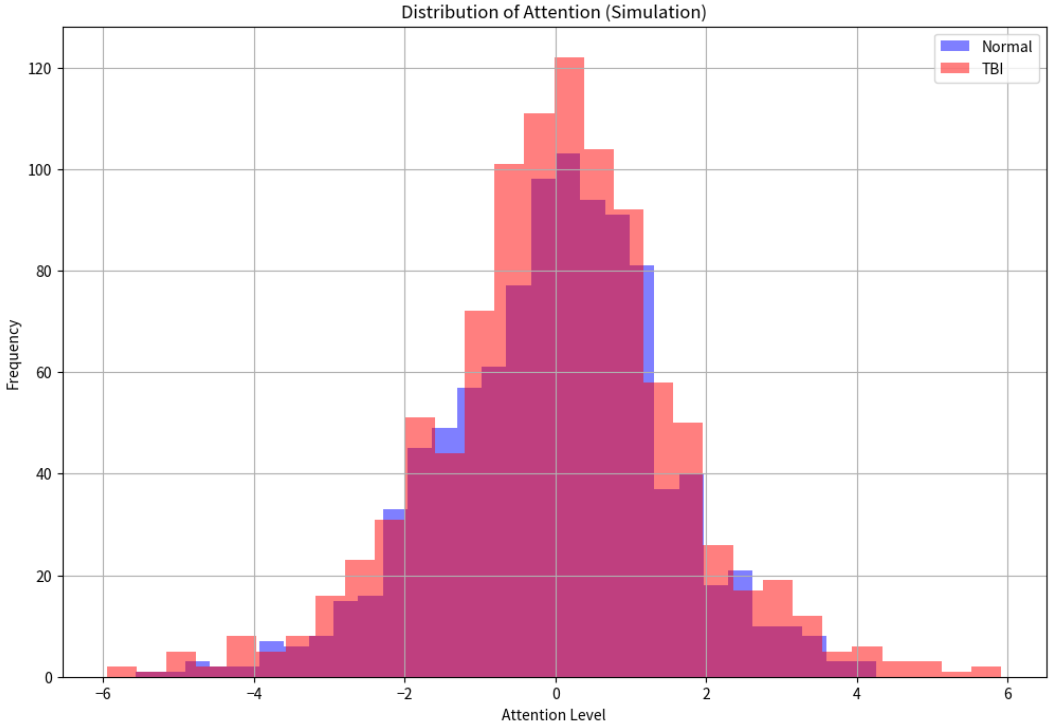
For both scenarios, we generate a series of sensory inputs and precision values. Sensory inputs represent the information that the brain receives from the environment, while precision values represent the brain's confidence in its predictions about these inputs.

In the normal scenario, sensory inputs are generated from a normal distribution with a mean of 0 and a standard deviation of 1, representing a typical range of sensory inputs. Precision values are generated from a uniform distribution between 0.5 and 1.5, representing a typical range of precision values.

In the TBI scenario, we assume that the brain's sensory inputs are more volatile and noisy, and its precision values are lower. This is represented by generating sensory inputs from a normal distribution with a mean of 0 and a higher standard deviation of 2, and generating precision values from a uniform distribution between 0.2 and 1.2.

Next, we calculate prediction errors for both scenarios. Prediction errors represent the difference between the brain's predictions about sensory inputs and the actual sensory inputs.

Finally, we calculate attention levels as the precision-weighted prediction errors. This represents the idea that attention is driven by the brain's confidence in its predictions and the discrepancy between its predictions and the actual sensory inputs.



The resulting plots show the distribution of attention levels for the normal and TBI scenarios. The blue histogram represents the normal scenario, while the red histogram represents the TBI scenario.

From the plots, we can see that the distribution of attention levels in the TBI scenario is wider and shifted towards higher values compared to the normal scenario. This suggests that after a TBI, the brain's attention levels can be more variable and generally higher, reflecting the increased volatility and noise in sensory inputs and the decreased precision. This could potentially lead to symptoms such as difficulty focusing, distractibility, and cognitive fatigue.

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