The Exhausted Brain Theory: An Energy-Based Framework for Understanding Visually Induced Motion Sickness

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Abstract: Visually Induced Motion Sickness (VIMS) poses a persistent challenge in various scenarios, from virtual and augmented reality (VR/AR) to transportation and simulation-based training. Existing theories, such as sensory conflict and postural instability, offer partial insights but fail to fully explain the metabolic and cognitive dynamics underlying VIMS. This paper introduces the Exhausted Brain Theory, which proposes that VIMS arises from excessive energy demands on the brain as it recalibrates internal models to resolve conflicting sensory inputs. Drawing from computational neuroscience, information theory, and energy metabolism, the theory highlights how sensory conflicts overwhelm neural processing, deplete energy reserves, and disrupt predictive coding mechanisms. We discuss implications for modeling, detection, and mitigation of VIMS, including energy-efficient VR design, targeted acclimatization protocols, and personalized interventions. By integrating diverse perspectives, this theory provides a unifying framework to advance understanding of VIMS and guide future research on its prevention and management.

1 INTRODUCTION

In 1835, Charles Darwin said "...I continue to suffer so much from sea-sickness, that nothing,[...], can make up for the misery..." (Dobie, 2019) and he is not alone. Motion sickness is also a problem that affects millions of people (Dobie, 2019). In this position paper, we use the term Visually Induced Motion Sickness (VIMS) as an umbrella term to encompass motion sickness, cybersickness, and simulator sickness. VIMS has been a persistent challenge since the advent of transportation and, more recently, virtual reality (VR) technologies, including even 2D videos. Despite centuries of study, a comprehensive understanding of its mechanisms remains elusive. Current theories, such as the sensory conflict theory (Reason, 1978b) and the postural instability theory (Riccio and Stoffregen, 1991), while valuable, fail to fully explain all aspects of VIMS, particularly its variability across individuals and situations.

VIMS manifests across a wide range of scenarios. In transportation, it affects passengers in cars, boats, airplanes, and even space vehicles, with symptoms ranging from mild discomfort to severe nausea, and the advent of autonomous vehicles introduces new challenges as passengers become more disconnected from vehicle control. In VR, augmented reality (AR), and mixed reality (MR) applications, users often experience it during immersive experiences, limiting the technology's potential in fields such as education, healthcare, and entertainment. VIMS affects military personnel and civilian trainees using high-fidelity simulators for aircraft, vehicles, and complex machinery. Even in everyday scenarios, users of smartphones and tablets can experience discomfort when viewing motion-rich content or using navigation apps. As 3D displays become more common in consumer electronics, cinema, and gaming, a broader population is exposed to potential visual discomfort and sickness.

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2 THEORETICAL BACKGROUND

2.1 Visually Induced Motion Sickness Theories

The Multisensory Integration Perspective (Gallagher and Ferrè, 2018) is one of the most recent frameworks for understanding VIMS. This perspective emphasizes the brain's adaptive processes and how they might be overwhelmed in environments with divergent stimuli. It proposes VIMS as the nervous system's challenge to appropriately weigh and integrate various sensory signals, and it is arguably an evolution of the Neural Mismatch model (Reason, 1978b; Oman, 1989), which is currently one of the most widely accepted theories for VIMS. Initially proposed for "motion sickness" alone and later applied to other forms of VIMS, the Neural Mismatch model posits that symptoms arise when there is a mismatch between sensory inputs, particularly between visual, vestibular, and expectations. For example, in virtual reality, the visual system may perceive motion, while the vestibular system detects no movement, leading to conflict and subsequent sickness. While this theory explains many instances of VIMS, it does not fully account for individual differences in susceptibility or why some sensory mismatches cause more severe symptoms than others, and mainly why these would inflict symptoms.

The Postural Instability Theory (Riccio and Stoffregen, 1991) proposes that VIMS occurs when an individual's balance, which is the body's main aim, is disrupted as a virtual space discomfort follows. Though some studies support this; with increased postural sway in those experiencing sickness in virtual environments, it does not explain all cases, especially in stationary, seated positions. Similarly, the Rest Frame Hypothesis (Prothero, 1998a) suggests the brain selects a "rest frame" or a set of stable visual references in the environment. It proposes that sickness occurs when there are conflicting cues about what should be considered stationary. This theory has led to practical interventions in virtual reality, such as adding fixed visual references to reduce sickness. Nevertheless, all these theories are only explanations for what triggers VIMS, and not why there would be a trigger in the first place.

In terms of symptoms, several evolutionary explanations have been proposed to explain how they are triggered. The Poison Theory (Treisman, 1977) suggests that the body interprets unusual sensory inputs as signs of poisoning, triggering nausea as a protective response. Another evolutionary perspective proposes that sickness symptoms serve as a negative reinforcement to discourage activities that create aftereffects harmful to locomotion and gaze stability (Guedry et al., 1998). These theories offer interesting perspectives on why sickness might occur; nevertheless, they can struggle to explain the full range of symptoms and individual variations and even the counter-productivity of some strategies in critical scenarios.

Each of these theories contributes valuable insights about VIMS, but none fully explains all aspects of the condition. They often complement each other, addressing different facets of the complex interplay between human physiology and technological environments. The limitations of these existing theories highlight the need for a more comprehensive unifying framework to understand and address VIMS across various scenarios.

We propose The Exhausted Brain Theory (EBT). A framework for understanding VIMS by integrating concepts from most previous theories, neuroscience, information theory, and energy metabolism. Our theory posits that VIMS results from an excessive energy demand placed on the brain when it attempts to rapidly recalibrate its internal models in response to unfamiliar or conflicting sensory inputs.

2.2 Information Theory and Computational Neuroscience

Information Theory, introduced by Claude Shannon (Shannon and Weaver, 1949), provides a mathematical framework for quantifying the transmission, processing, and storage of information, and evaluating the efficiency of encoding schemes. It presents important concepts such as Entropy (H), Mutual Information (I), and Channel Capacity (C), which quantify the amount of information produced by a data source and the reliable transmission capacity of this information. These concepts provide the theoretical underpinnings for understanding information processing in various systems, including the human brain.

The brain, as an intricate information-processing system, can be analysed through the lens of Information Theory. Neurons communicate via electrical impulses, with synaptic connections facilitating the transmission and transformation of information. Neural coding encompasses both rate coding and temporal coding, where either the firing rate of a neuron or the timing of spikes carry information. These mechanisms allow the brain to represent and process diverse stimuli efficiently.

In sensory processing, the Efficient Coding Hypothesis suggests that sensory systems are optimized to represent information efficiently, minimizing redundancy, and maximizing information transmission. This principle is evident in phenomena such as edge detection in the retina, which reduces redundant visual information to conserve energy and processing capacity.

The concepts of Predictive Coding and the Free Energy Principle (Friston, 2010), introduced by Karl Friston, present a possible explanation of how the brain processes information. Predictive Coding posits that the brain continually generates predictions about sensory inputs and updates its internal models based on prediction errors. The Free Energy Principle extends this idea, stating that the brain seeks to minimize free energy (a measure related to surprise or prediction error) to maintain a stable state. These principles highlight the brain's constant effort to balance information processing demands with energy availability, a crucial consideration given the high metabolic cost of neuronal activity.

2.2.1 Biological Signal Processing

The free-energy principle (Friston, 2010) proposes that self-organizing systems maximize information between sensory and internal states by selectively sampling expected sensory inputs. This principle unifies the Bayesian Brain Hypothesis, Efficient Coding Principle, and Cell Assembly theory, suggesting the brain optimizes energy efficiency by creating and adjusting reality models through neuronal group changes—aligning with observed brain topology (Ma et al., 2021).

Trujillo (Trujillo, 2019) found experimental evidence that mental model adjustments increase energy consumption and subjective exhaustion. The brain develops multisensory integration through early-life cross-integration training (Xu et al., 2012), enabling mental maps crucial for spatial awareness (Hasselmo and Stern, 2013; Hughes et al., 2014; Allen et al., 2016). Honey et al. (Honey et al., 2012) revealed complex sensory integration involving slow-firing "information accumulator" neurons (0.1Hz), while Kok et al. (Kok et al., 2017) demonstrated that expectations preactivate sensory templates in the brain.

Neural communication is metabolically expensive (Laughlin, 2001; Attwell and Laughlin, 2001; Lennie, 2003), consuming 35 times more energy than information processing (Levy and Calvert, 2021). Lower firing rates (Koch et al., 2006) and weakly active cells (Sarpeshkar, 1998) reduce energy costs, although redundancy increases the cost per bit (Laughlin, 2001). Spatial awareness requires dense, narrow-field cells (Sterling, 2004; Wassle and Boycott, 1991) with low information rates to minimize costs (Koch et al., 2006).

Brain imaging reveals that vestibular stimulation reduces visual cortex blood flow (Gallagher and Ferrè, 2018; Deutschländer et al., 2002; Wenzel et al., 1996), while optic flow deactivates vestibular areas (Bense et al., 2001). This apparent energy waste (Christie and Schrater, 2015) may indicate neuronal group decoupling for reconfiguration.

The visual system is very energy expensive; neural activity between the brain and the retina creates a high metabolic demand. Energy is necessary for every signal sent, and densely packed neurons are constantly active (Laughlin, 2001). For mammals, 50% of the total energy consumed by the brain is from signaling, and in the cortex area, it represents 80% (Laughlin, 2001).

The outputs of two adjacent photoreceptors often measure light coming from the same object and therefore send very correlated signals. Thus, simply transmitting their redundant information further as the output of the photoreceptors would be inefficient, since the same information would be sent multiple times (Roland, 1999). However, in the presence of noise, some redundancy can be helpful to (1) identify information corruption and (2) correct errors. Thus, animal structures such as the retina of vertebrates are made up almost exclusively of non-spiking neurons, which appear to be used to eliminate redundancies and noise while boosting the remainder (Burton, 2000).

Because light varies widely in intensity and photoreceptors are limited to the dynamic range, sensory adaptation is a solution (Niven and Laughlin, 2008). For instance, in insects, when receiving a constant input, the photoreceptor will keep a tonic activity (constant activation), but the neuron communication will be phasic, allowing for the amplification and filtering of noises. At least in insects, the output of the messaging system among their neurons matches the probability curve that maximizes information (Burton, 2000). Moreover, humans have been observed to see signals when pacemaker neurons are in specific phases and miss in the opposite phase (Busch et al., 2009).

After the basics of signal reception, Field (Field, 1994) argues that natural images follow certain patterns, which he describes as "sparse" (which are similar to the filters in a CNN) and that our photoreceptors have arrays that activate specifically upon finding these patterns, thus even though identifying all possible patterns requires a lot of cells, individual images only activate a few. And then, through this method, cognitive tasks such as learning would be facilitated because there will be little ambiguity (Burton, 2000). Naturally, this process can be changed because it has been experimentally seen that the receptive fields of cortical cells are dynamic.

To summarize, because the visual system demands a lot of energy, it must come up with ways to be robust, effective, and energy-efficient; thus, it will come up with representations of the world, which can later be altered.

2.2.2 Biologically Inspired Computing

To delve deeper into the neural computations underlying these principles, models such as Hopfield Networks and Boltzmann Machines offer valuable insights. Hopfield Networks are recurrent artificial neural networks that function as content-addressable memory systems. They store information in a distributed manner and retrieve it through an energy minimization process. The network dynamics settle into stable states (local minima of an energy function), representing stored patterns (Vallejo and Bayro-Corrochano, 2008), (Kumar and Satsangi, 1992), (Abubakar, 2021), (Murthy and Gabbouj, 2015).

Boltzmann Machines extend this concept by introducing stochasticity into neuron activation, allowing the network to explore various states and escape local minima. They are capable of learning internal representations and modeling complex probability distributions, with an energy function (Liu and Chen, 2011), (Barra, 2012), (Agliari, 2013), (Fukai, 1992).

3 THE EXHAUSTED BRAIN THEORY

These computational models reflect the brain's efforts to reach low-energy states through synaptic adjustments, mirroring how neural networks adapt to minimize prediction errors (Friston, 2010). In the context of the EBT, they exemplify how processing conflicting sensory inputs requires additional energy as the brain strives to settle into a new stable state when confronted with discrepancies. As such, in this case, we will consider variations in signal that cause abnormal activation as conflicting signals.

For example, in virtual reality or motion simulation, the usual correspondence between visual, vestibular, and proprioceptive input is disrupted. This mismatch increases the entropy of sensory input as the brain faces greater uncertainty. Consequently, the brain must process more information to resolve this uncertainty, leading to higher entropy. This increased entropy results in higher information processing demands (Laughlin, 2001). The mutual information between sensory inputs and internal models decreases due to the conflict, as the brain's predictions no longer match incoming data.

To minimize prediction errors, the brain attempts to update its internal models, a process that requires processing additional information and consumes significant energy (Christie and Schrater, 2015). The metabolic cost of these processes can lead to energy depletion. This processing can increase entropy and updating internal models is a metabolically demanding task, with neuronal firing and synaptic plasticity consuming energy in the form of adenosine triphosphate (ATP). If the energy demand exceeds supply, the brain experiences a form of "exhaustion," manifesting as symptoms associated with VIMS, such as nausea and dizziness—akin to the fatigue experienced during excessive physical exercise (see Figs 1 and 2).

Channel capacity limits also play a role in VIMS. The neural pathways have limited capacity, and excessive sensory information can overwhelm these channels, causing delays or errors in processing. Additionally, conflicting inputs can reduce the effective signal-to-noise ratio, making it harder for the brain to extract meaningful information without expending more energy (Trujillo, 2019).

From the perspective of Predictive Coding, VIMS can be understood as a failure of the brain's predictive

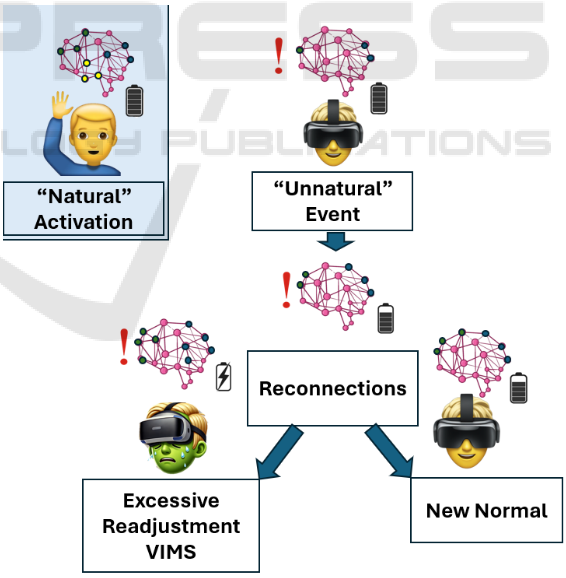

Figure 1: A visual representation of the EBT. The user interacts with an unnatural environment, such as a VR headset, leading to changes in the activation patterns of neurons. This disruption requires reconnections and neural recalibration to achieve a 'new normal.' If this recalibration occurs efficiently, symptoms of Visually Induced Motion Sickness (VIMS) are avoided. However, when the neural readjustment is excessive or prolonged, the resulting energy depletion manifests as VIMS. Neuron activations are represented by differently colored circles.

mechanisms. Its capacity is constrained by metabolic resources, which is why prolonged exposure to sensory conflicts without adequate energy supply can lead to persistent symptoms. The discrepancy between the expected and actual sensory inputs leads to higher prediction errors, which are computationally and energetically costly to resolve (Friston, 2010). The theory also accounts for individual susceptibility to VIMS, as variations in metabolic efficiency and neural processing capacity can affect one's ability to manage increased informational entropy.

Further insights come from examining the brain's oscillatory activity and spatial representations. Theta rhythms, neural oscillations in the 4–8 Hz frequency range, are prominent during active behaviors like exploration and navigation. They are associated with memory encoding, spatial navigation, and sensorimotor integration (Ravassard, 2013), (Romani, 2011), (Zielinski et al., 2019) . Place cells, neurons in the hippocampus, become active when an individual is in or moving toward a specific location, forming a cognitive map of the environment.

In virtual environments, sensory conflicts can disrupt normal theta rhythm patterns and place cell activity, impairing the synchronization of neural networks involved in spatial cognition. This desynchronization requires additional neural processing to resolve, increasing energy consumption. Moreover, the brain's effort to recalibrate its spatial maps in response to inconsistent cues aligns with the energy demands described in the EBT—costly, as a parallel can be drawn from a gradient descent, in which closer values are easier to achieve.

The concept of Neural Manifolds and Latent Spaces provides a framework for understanding how the brain represents high-dimensional sensory inputs in a low-dimensional space, capturing the essential features while reducing complexity. When sensory inputs are conflicting or novel, this mapping becomes less efficient, requiring more energy to process and interpret the data. Adjusting these internal representations is metabolically demanding, contributing to the symptoms of VIMS (Monaco, 2019), (Herweg and Kahana, 2018), (Lu, 2020).

One of the advantages of this framework is that it does not require the brain to have an area dedicated to deciding when VIMS should appear and does not impose new systems or differentiated systems to interpret different inputs and detect poisoning. Moreover, it is well accepted that "neurons that fire together wire together", and the ones that do not lose their connections.

This framework also highlights the importance of energy efficiency in neural processing. It underscores the need for virtual environments and technologies to account for the brain's capacity limitations and metabolic constraints, potentially guiding the development of interventions and design principles to mitigate VIMS.

In summary, the EBT synthesizes concepts from Information Theory, computational neuroscience, and physiological observations to explain how VIMS arises from the brain's overexertion due to conflicting sensory information and the consequent energy depletion. It provides a unifying framework that accounts for individual variability and offers pathways for future research and practical solutions.

3.1 Evidences for the Theory in Literature

Empirical observations and research findings provide evidence supporting the EBT's proposition that VIMS results from brain overexertion and energy depletion during conflicting sensory processing. Studies have shown that performing activities with VR headsets leads to higher heart rates and increased calorie burn compared to the same activities without VR, suggesting increased physiological energy expenditure (Xu et al., 2020). EEG studies indicate that task complexity correlates with cybersickness (Sepich et al., 2022).

The correlation between sensory conflict and neural effort is supported by EEG research that demonstrates higher P3 amplitudes in susceptible individuals responding to sensory mismatches (Ahn et al., 2020). This suggests increased cognitive demand and energy expenditure as the brain attempts to resolve conflicting sensory information. Participants who experience symptoms also show notable changes in autonomic responses, indicating heightened energy demand and stress responses.

Babies and the elderly appear less susceptible to traditional motion sickness, possibly due to differences in neural pathways or sensory reliance, babies for not having the pathways defined and the elderly for having a lower dependency on vestibular cues (Schmäl, 2013), thus neither needing readjustment. Susceptibility factors linked to metabolic processes further support the theory. Genetic factors are often associated with glucose imbalance rather than vestibular dysfunction, suggesting that efficient energy utilization is crucial to managing sensory conflicts (Hromatka et al., 2015).

The impact of nutrition and sleep reinforces the EBT. Studies have shown that maintaining stable blood sugar can mitigate symptoms, while sleep deprivation, which impairs glucose metabolism and cognitive function, has been linked to increased sus-

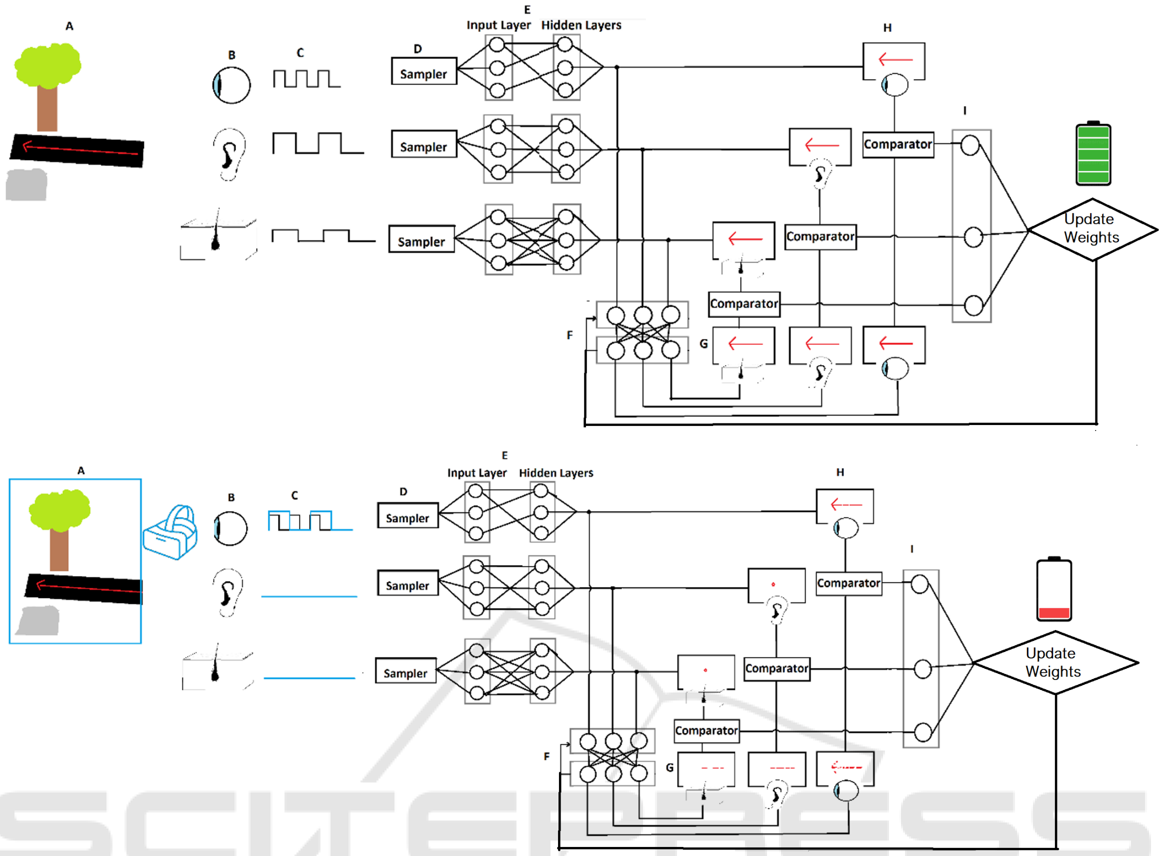

Figure 2: Top - Natural processing: Environmental signals (A) are captured by sensors (B), sampled (C,D), processed (E), compared against predictions (G,H) based on previous states (F), and weighted (I) for continuous model updating. Bottom - VR processing: Similar pathway but with artificial signals leading to sampling mismatches and corrupted observations, requiring additional energy for recalibration and processing.

ceptibility (Kaplan et al., 2017). The sopite syndrome, characterized by drowsiness and fatigue following motion exposure, aligns with the theory, suggesting the brain requires rest to recover and recalibrate its energy balance (Matsangas and McCauley, 2014).

Cognitive load and learning limitations provide further evidence. Participants using VR headsets with higher sickness incidence showed lower rates of knowledge acquisition, suggesting that the brain's resources are diverted to manage sensory conflicts (Makransky et al., 2019). The effectiveness of mitigation strategies, such as gradual acclimatization and nutritional interventions, supports the energy-based explanation (Graybiel and Wood, 1969; Graybiel et al., 1969).

Physiological measurements during exposure, including altered blood flow in brain regions and electrogastrographic changes, indicate metabolic activity changes and systemic responses to neural overexertion (Gavgani et al., 2018). These findings collectively support the EBT, demonstrating that VIMS is closely linked to the brain's energy dynamics during sensory conflicts. This comprehensive explanation offers a foundation for developing targeted mitigation strategies focused on managing cognitive load and supporting neural energy requirements.

3.2 Relation with Previous Theories

The EBT can encompass other theories of technology sickness because it posits that the brain's adaptation to new sensory inputs requires significant energy, leading to an "exhausted" state when demand exceeds supply (see table 1). The Cue Conflict Theory (Irwin, 1952; Bonato et al., 1990) suggests sickness arises from mismatches between sensory inputs (visual, vestibular, proprioceptive). This aligns with the EBT because resolving these conflicts necessitates neural rewiring, which is energy-intensive. Similarly, the Rest Frame Hypothesis (Chang et al., 2013; Lin et al., 2017) and Postural Instability Theory (Riccio and Stoffregen, 1991; Villard and Flanagan, 2008) focus on the brain's reliance on stable reference frames, which can be integrated because recalibrating these frames in response to conflicting cues in virtual environments demands additional energy.

The Negative Reinforcement and Poison Theories also fit within this framework. The former proposes that sickness is a deterrent against potentially harmful activities (Bowins, 2010), while the latter suggests that it is an evolved response to perceived toxins (Treisman, 1977; Nalivaiko et al., 2004). Both align with the EBT because avoiding energy-depleting situations would be evolutionarily advantageous and the residues of energy-intensive activity can be harmful. Lastly, Sensory Rearrangement Theory (Reason, 1978a; Oman, 1982), which posits that the brain updates paired sensory information during conflicts, and Multisensory Integration perspectives (Gallagher and Ferrè, 2019; Kaliuzhna et al., 2015), which emphasize the brain's weighting of different sensory cues, are encompassed because these processes require energy to modify neural pathways and synaptic connections. Therefore, the EBT provides a unifying framework by explaining the energy demands underlying these various theoretical perspectives.

3.3 Mitigation Through the Theory Lenses

Several techniques can be applied to reduce VIMS, especially in VR. For example, techniques such as the VRCockpit (Chen et al., 2022), PlaneFrame (Monteiro et al., 2020), and Rest Frames (Monteiro et al., 2018b; Monteiro et al., 2018a; Prothero, 1998b; Shi et al., 2021) offer consistent visual or physical cues that help the brain establish stable reference frames, easing the energy-intensive process of recalibration (Wienrich et al., 2018).

Techniques that minimize sensory discrepancies directly address the root cause of energy drain. For example, field-of-view reduction (FOV) (Fernandes and Feiner, 2016) and blurring (Kobayashi et al., 2015) limit visual information, particularly in peripheral vision, which is the main way the brain detects speed visually. As a result, the brain has to process fewer conflicting cues, thereby reducing energy expenditure (Lin et al., 2002).

Increasing Fidelity is an approach that can either do wonders or have the opposite desired outcomes. Enhancing the realism of virtual environments by adding congruent vestibular, such as higher resolution and frame rate (Wang et al., 2023b; Wang et al., 2022a) or proprioceptive feedback, such as vibration or wind (Wang et al., 2022b; Zhao et al., 2024), reduces sensory mismatches, when done well. This can minimize the need for the brain to reconcile discrepancies, thus conserving energy (Suzuki et al., 2019). However, presenting even more discrepant information can exacerbate the symptoms (D'Amour et al., 2017).

Techniques that improve the brain's efficiency in handling sensory input can indirectly reduce energy consumption by optimizing information processing. For instance, gradual exposure and adaptation by and incremental introduction of users to virtual environments or motion stimuli allows their brain to gradually adapt and rewire neural pathways (Graybiel et al., 1969). This staged process avoids a sudden surge in energy demand, enabling more efficient learning and reducing sickness over time. Even cognitive training, with targeted exercises, can enhance the brain's ability to process conflicting sensory information. By improving efficiency, the brain can require less energy to handle sensory discrepancies, mitigating sickness (Nalivaiko et al., 2018).

3.4 Implications, Predictions, and Future Work

The EBT provides a foundation for advancing the modeling, research, treatment, detection, and mitigation of VIMS.

The brain's energy demands during sensory conflicts and the resulting metabolic imbalances can be explored using mathematical models and simulations. These models could predict susceptibility to VIMS by analyzing brain connectivity patterns and metabolic rates. By focusing on specific regions and behaviors, the accuracy of these predictions has the potential to

Table 1: Summary of what each theory accounts for. OK symbolizes that the theory accounts for that component at least partially.

What the theories account for	Sickness Triggers	Individual Susceptibility	Signal Intensity	Why Triggers Cause Sickness	Adaptation	After-Effects
Cue Conflict Theory	OK		OK			
Rest Frame Hypothesis	OK		OK			
Postural Instability	OK	OK	OK	OK		
Negative Reinforcement	OK	OK	OK	OK		
Poison Theory	OK	OK	OK	OK		
Sensory Rearrangement	OK		OK		OK	
Multisensory Integration	OK	OK	OK		OK	OK
Exhausted Brain Theory	OK	OK	OK	OK	OK	OK

improve significantly.

Furthermore, artificial neural networks could simulate VR scenarios to identify those most likely to induce VIMS. By tracking the number of iterations required for the network to ”readapt” to conflicting inputs, designers could optimize environments to reduce VIMS triggers. For example, a bio-inspired Spiking Neural Network trained for self-location and mapping—using accelerometer and video data—could later be exposed to new VIMS-like ”noisy” data. The time required for readaptation in response to this interference could serve as a guideline for detecting VIMS-triggering environments.

The development of a standard for movement parameters and dimensions in XR environments could also facilitate broader adoption. Mental training acquired in one environment might transfer to another application. However, applications with uneven movement patterns or inconsistent frame optimization could still cause users to struggle. For instance, in a single application, fluctuating frame rates are more likely to induce sickness. This theory highlights that individual differences in sensory integration and metabolic efficiency influence susceptibility to VIMS. It also underscores that adaptation to one type of VIMS-inducing environment may not guarantee immunity in others, emphasizing the need for tailored acclimatization.

Given this context, we can expect users who present better spatial acuity and use several cues for self-location to suffer more from VIMS than those with poor self-location.

Using EEG to synchronize refresh rates with neuronal activation frequencies—-potentially even varying by screen area—-may reduce VIMS. This approach could allow for better resource allocation, as not all screen regions may need simultaneous updates.

Developing specific tools to measure energy expenditure and adaptation processes could improve VIMS detection. For example, functional near-infrared spectroscopy (fNIRS) or similar non-invasive methods could help analyze neural and metabolic responses. Recording blood glucose levels before and after VR exposure, where ethically permissible, could reveal metabolic changes linked to VIMS. Participants could also be asked about conditions affecting glucose processing, such as diabetes, pancreatic disorders, or body mass, to refine the collected data.

Given the nature of the theory, it would theoretically be possible to assess an individual's susceptibility by analyzing information beyond the exposure itself. This could involve determining the strength of the coupling between their visual and vestibular systems, as well as evaluating the amount of energy required to readjust when faced with a different form of conflict. In a longitudinal study, as the degradation of the vestibular system slowly causes the decoupling of the two information systems, VIMS should be less present (considering all other metabolic aspects remain constant).

For long-term studies or repeated exposure, introducing a ”Day-0” adaptation protocol for users and participants would be ideal. This protocol would allow individuals to acclimate to new simulators and HMDs, ensuring that they experience applications as intended. Structured acclimatization frameworks might include 1) Exercises to ”decouple” visual and vestibular senses. 2) Gradual exposure to VIMS-inducing content, starting with simpler environments (e.g., figure outlines) and increasing complexity incrementally. 3) Training strategies to optimize brain energy usage, akin to stepwise progression in athletic training. 4) Adequate nutritional intake.

Detecting when users are ready to engage in learning activities within VIMS-inducing environments could enhance the effectiveness of these settings. Ensuring habituation before introducing cognitive tasks could prevent overload and maximize learning outcomes. Short-term studies should consider using participants who are already acclimated to the environment to avoid skewing the results. Moreover, studies showing minimal learning differences in VR may underestimate its potential, as new exposure to VR could hinder outcomes. This suggests that some findings that consider VR ineffective for learning might stem from studies that are too short (Monteiro et al., 2024; Barrett et al., 2023; Makransky et al., 2019).

The EBT could also inform new health and safety guidelines for prolonged XR and simulator use, particularly in professional contexts where extended use is required. Additionally, it raises important considerations for children's use of XR and simulators. As ”virtual natives,” children exposed to XR environments may develop long-term advantages, such as more adaptable movement pathways and increased neural connections, akin to the benefits of early language acquisition, once thought to be a disadvantage. This also means that it is possible that some people could never adapt when exposed to just ”normal” use.

3.5 Testable Hypotheses

To validate the EBT, several testable hypotheses can be proposed. These hypotheses aim to explore the relationship between energy dynamics, sensory conflicts, and individual variability in the context of Visually Induced Motion Sickness.

H1: Individuals performing cognitively demanding tasks during exposure to a sensory conflict-inducing VR environment will experience higher levels of VIMS compared to those in less demanding tasks. A controlled experiment could compare VIMS to physiological markers of energy expenditure.

H2: Gradual acclimatization to VR environments will reduce VIMS symptoms over time compared to abrupt exposure to complex environments. This hypothesis could be explored in a longitudinal study by comparing symptoms between participants exposed to incremental versus sudden increases in the complexity of the VR session.

H3: Individuals with a higher baseline efficiency in predictive coding will experience less severe VIMS in sensory-conflicting VR environments. Predictive coding efficiency could be measured using EEG patterns or behavioral tests of sensory integration and correlated with VIMS symptoms.

H4: Increasing the sensory fidelity of VR environments, such as by adding congruent vestibular feedback in an extremely precise way, will reduce VIMS symptoms compared to conditions with sensory mismatches; otherwise, it will cause worse symptoms. This could be tested by comparing symptoms and EEG markers such as theta rhythm desynchronization in conditions with and without synchronized vestibular feedback.

H5: Participants with higher aerobic fitness levels will exhibit lower VIMS susceptibility, as better metabolic efficiency could buffer against the energy depletion associated with sensory conflicts.

H6: Participants with more stable theta rhythms during VR exposure will experience fewer VIMS symptoms. EEG data could be used to examine theta rhythm stability and its relationship with VIMS severity across varying sensory conflict levels.

These hypotheses provide a framework for empirical validation of the EBT and should be tested using techniques that detect VIMS within the experiment (Wang et al., 2020; Wang et al., 2023a; Monteiro et al., 2021).

3.6 Limitations

One limitation of this work is its correlational nature, as it does not include empirical evidence derived from original experiments. While correlations cannot establish causation, this does not diminish the validity of the framework presented. Similar research in this field also relies on the existing literature and observational studies, and other recognized theories are untestable. Furthermore, the correlations drawn here are supported by multiple reliable sources, lending credibility to the insights. Importantly, this work is intended as a foundation for future research, providing a framework that can guide experiments designed to either support or challenge this theory.

Another limitation of this paper is that we do not delve into the specifics of how glucose is processed or explore the broader metabolic processes in detail. Consequently, the root cause of the issue might be related to the energy demand process rather than the energy demand itself. However, this lies beyond the scope of the paper and the technical expertise of the researchers. Despite this limitation, related studies still support the overall association between energy and VIMS. The authors remain open to alternative interpretations, e.g., such as the possibility that the problem might stem from residual effects of the readjustment process rather than the readjustment itself.

4 CONCLUSION

The EBT provides a comprehensive and unifying framework to understand the phenomenon of VIMS. By emphasizing the brain's metabolic demands and energy limitations during sensory conflict resolution, the theory integrates insights from established perspectives, such as sensory conflict, postural instability, and multisensory integration. It highlights how the brain's effort to recalibrate internal models in response to conflicting sensory inputs can lead to energy depletion and, consequently, VIMS symptoms.

This energy-based approach not only explains individual susceptibilities to VIMS but also accounts for the variability in symptoms across scenarios and technologies. By framing VIMS as a product of the brain's effort to minimize prediction errors and maintain internal stability, the theory bridges the gap between neurophysiology, computational neuroscience, and energy metabolism. It underscores the importance of designing energy-efficient virtual environments and personalized interventions to reduce the cognitive and metabolic strain associated with immersive technologies.

Furthermore, the EBT lays the groundwork for future research aimed at modeling, detecting, and mitigating VIMS. From developing tools to measure neural and metabolic responses to designing acclimatization protocols and energy-aware XR systems, the theory inspires practical solutions to a critical challenge in the adoption of emerging technologies. As immersive environments become increasingly integral to education, healthcare, and entertainment, understanding and addressing the underlying causes of VIMS is essential for their safe and effective use.

In conclusion, the EBT not only enriches our understanding of VIMS but also opens new avenues for research and innovation, offering a pathway toward enhancing the accessibility and usability of virtual and augmented reality technologies.

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