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The Neurodynamic Impact of Vitamin D Deficiency on Language Processing: Insights from Oscillatory and Network Neuroscience

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Abstract

Language processing is a sophisticated cognitive activity supported by dynamic interactions within extensive brain networks. Recent interdisciplinary research suggests that vitamin D, in addition to its traditional role in calcium regulation, may also influence brain function by modulating neuronal excitability, synaptic plasticity, and neurotransmission. The precise effect of vitamin D insufficiency on the neurodynamic structure of language is yet inadequately comprehended. This study intends to rigorously analyze the correlation between vitamin D levels and the oscillatory and connective characteristics of language-related neural networks through a narrative and critical review methodology. Literature was obtained from prominent scientific databases and evaluated thematically, concentrating on molecular processes, brain oscillations, and functional connections. The results demonstrate that vitamin D insufficiency correlates with decreased beta and gamma oscillatory power, reduced theta coherence, and impaired functional connectivity between critical language regions, including Broca's and Wernicke's areas. These disruptions indicate a deviation from optimal brain rhythms, which may hinder linguistic integration and predictive processing. The study emphasizes the need for longitudinal and interventional investigations, combined with computational modeling based on neurophysics, to further clarify these pathways. These discoveries enhance the understanding of how systemic biological variables influence cognitive networks and may guide future efforts for the early detection and intervention of language-related illnesses.

Keyword: Vitamin D Deficiency; Neural Oscillations; Language Networks; Functional Connectivity; Neurophysics

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INTRODUCTION

One of the most complex and defining features of the human mind is language. It aids in abstract thinking, socialization, cultural transmission, and making sense of the world. Researchers have examined the neural basis of language in detail and identified a wide-ranging network of cortical and subcortical areas that support various language tasks, including phonological processing, syntactic parsing, semantic integration, and pragmatic inference [1], [2]. Broca's area, Wernicke's area, the angular gyrus, and the arcuate fasciculus are all components of large, dynamic neuronal networks that collaborate to coordinate activity across a wide range of spatial and temporal dimensions.

Recent progress in systems neuroscience and computer modeling has shifted the focus from specific brain regions to the functioning of neural networks. Increasingly, people are recognizing language processing as a novel trait that emerges when different brain regions synchronize and connect functionally [3], [4]. Theta (4–8 Hz), beta (13–30 Hz), and gamma (30–100 Hz) neural oscillations are linked to different parts of language, such as working memory, grammatical prediction, and semantic binding [5], [6], [7], [8], [9] These oscillations help different parts of the brain work together and stay in sync, which lets the brain process language data right away.

Neurophysics is a field that utilizes physical and mathematical models to investigate the functioning of neural systems. This view of language aligns with what neurophysiology suggests. The brain is a nonlinear, self-organizing system from a neurophysical point of view. Its cognitive functions stem from the interactions of many subsystems, which are limited by biophysical factors [10]. Researchers have employed concepts such as phase synchronization, criticality, and network topology to elucidate the mechanisms underlying neural activity, perception, memory, and language. Language is not just a symbolic or computational process in this case; it is a biophysical phenomenon that depends on how well and how quickly neural dynamics work.

At the same time, an increasing number of people are interested in understanding how hormones, micronutrients, and metabolic regulators influence brain function. Vitamin D has become one of the most significant factors affecting how neurons function. Vitamin D is now recognized as a neurosteroid that influences brain development, synaptic plasticity, neurotransmitter synthesis, and neuroimmune regulation [11], [12]. It was once thought to be only necessary for calcium homeostasis and bone health. Vitamin D receptors (VDRs) and the enzyme 1α-hydroxylase, which changes vitamin D into its active form, are found in many parts of the brain that are important for thinking, such as the prefrontal cortex, hippocampus, and basal ganglia [13], [14], [15], [16].

Vitamin D deficiency has been linked to several neuropsychiatric and neurodegenerative disorders, such as depression, schizophrenia, Alzheimer's disease, and cognitive decline in older people [17], [18]. Animal studies have shown that a lack of vitamin D impairs the growth of new neurons in the hippocampus, alters the functioning of synapses, and increases oxidative stress [19], [20], [21]. These links are supported by the studies mentioned. Most of this research has focused on how vitamin D affects overall cognitive outcomes. However, new evidence suggests that it may also affect language-related functions, especially in children with developmental disorders and older adults who are at risk of cognitive decline [22], [23].

There is a significant amount of research on vitamin D and brain health; however, the exact mechanisms by which a lack of vitamin D affects the neural dynamics and connectivity of language networks remain unclear. Most studies conducted so far have focused on changes in brain structure or general cognitive issues, without examining the neurophysiological processes underlying language problems. Additionally, studies that examine neural activity often employ broad measures, such as global brain volume or resting-state connectivity, which may overlook the small oscillatory patterns and network interactions crucial for language processing.

There is also a lack of theoretical integration between fields. Vitamin D research is often done in the fields of clinical nutrition or neuropsychology, while language network studies are usually based in cognitive neuroscience or computational modeling. Because of this disciplinary split, there is a conceptual gap: even though it is known that vitamin D affects calcium signaling, neurotransmitter release, and synaptic plasticity, all of which are important for neural oscillations, not many studies have tried to link these molecular mechanisms to changes in oscillatory dynamics or functional connectivity in language circuits.

Additionally, there is a lack of critical synthesis of the existing research in the literature. Some studies have found that individuals with low vitamin D levels exhibit different EEG rhythms or disrupted functional connectivity; however, these results are often inconsistent and employ varying methods. It is challenging to draw generalizable conclusions because the samples, vitamin D levels, cognitive tasks, and neuroimaging methods used vary. It is difficult to assess the strength of the evidence, identify areas of agreement or disagreement, and formulate clear hypotheses for future research without a systematic and critical review.

Ultimately, we require conceptual frameworks that can facilitate both theoretical modeling and real-world research. Without these kinds of frameworks, we can't determine how a lack of vitamin D might affect language function at the systems level or devise targeted interventions that work on specific neural mechanisms. Because language networks are so complex and vitamin D has numerous effects on the brain, we require an interdisciplinary approach based on neurophysiology.

This review aims to fill these gaps by providing a narrative and critical summary of the research on vitamin D deficiency and its potential impact on the neurophysiology of language networks. We examine how vitamin D levels may impact the oscillatory dynamics and functional connectivity of neural systems involved in language processing. We propose an integrative framework that links changes in brain network behavior to neurobiological alterations associated with vitamin D. This framework is grounded in evidence from neuroimaging, electrophysiology, molecular neuroscience, and computational modeling. We have three goals:

1. To put together the most recent research on how vitamin D affects neural oscillations and connectivity, with a focus on brain areas and networks that are important for language.
2. To carefully look at the strengths and weaknesses of the methods and theories used in existing studies, pointing out any inconsistencies, biases, and gaps in the literature.
3. To suggest new areas of research based on neurophysical principles, such as experimental designs, computer models, and possible clinical uses.

This review helps us better understand how systemic biological factors, such as a lack of vitamin D, can affect complex cognitive functions like language by examining them from a neurophysiological perspective. It also demonstrates the value of integrating ideas from physics, neuroscience, linguistics, and nutrition. The primary objective of this work is to stimulate new research into the biological basis of language and to facilitate the development of methods for identifying, preventing, and treating language-related disorders at an early stage.

METHOD

This study employs a narrative and critical review design to synthesize and evaluate the current literature on the relationship between vitamin D deficiency and neurodynamic processes underlying language processing. A narrative review facilitates broad conceptual exploration [24], whereas a critical review enables a deeper analysis and evaluation of selected studies [25]. The review is based on an interdisciplinary framework that brings together ideas from neurophysics, cognitive neuroscience, nutritional neurobiology, and systems theory. The research was conducted to ensure that it covered a wide range of topics and provided detailed information, while remaining clear and analytical.

Research Design

The review employs a narrative-critical approach, which is ideal for examining complex, interdisciplinary subjects that are not yet ready for meta-analytic synthesis. Cross-disciplinary reviews benefit from flexible, mixed-method approaches, where narrative elements help clarify concepts and contextualize findings before a meta-analysis is possible [26]. Systematic reviews aim for comprehensive coverage through predefined, standardized methods, ensuring consistency and reproducibility. In contrast, narrative reviews enable a more flexible and interpretive engagement with the literature, offering greater freedom for critical analysis and theoretical development [27], [28]. Such an approach is critical in new fields where combining theories and mapping concepts is just as important as gathering data.

The primary aim of this review is not merely to summarize existing findings, but also to critically examine the underlying assumptions, methodologies, and theoretical frameworks that inform those results. This dual focus on synthesis and critique is intended to identify conceptual gaps, methodological inconsistencies, and emerging areas that warrant further investigation.

Data Sources

A thorough search of major academic databases, including PubMed, Scopus, Web of Science, and Google Scholar, revealed relevant literature. We chose these databases because they encompass a wide range of biomedical, neuroscientific, and interdisciplinary research. We found more sources by citation tracking and reference chaining (looking at the bibliographies of important articles) to make sure we included important and high-impact studies the search strategy employed both controlled vocabulary (such as MeSH terms) and free-text keywords. There were many search terms, such as "vitamin D deficiency" or "hypovitaminosis D", "brain oscillations," "neural dynamics," or "functional connectivity", "language processing," "language networks," or "aphasia", "neurophysics," "computational neuroscience," or "biophysical modeling" The search only looked for peer-reviewed journal articles that were written in English. There were no restrictions on the publication date, allowing both old and new contributions to the field to be included.

Data Collection Instruments

Since this study is literature-based, data collection was conducted using a structured literature matrix designed to systematically extract and organize relevant information from each source. The matrix included fields such as: type and design of the study (e.g., clinical, experimental, or computational); characteristics of the population or sample (such as age, health status, and vitamin D levels); neuroimaging or electrophysiological methods employed (e.g., EEG, fMRI, or MEG); approaches to measuring neural dynamics (such as phase coherence or oscillatory power); types of connectivity assessed (functional, practical, or structural); language-related outcomes (e.g., comprehension, fluency, or naming); key findings and conclusions; methodological strengths and limitations; and theoretical frameworks or conceptual underpinnings. This structured approach facilitated a side-by-side comparison of studies, enabling the identification of recurring patterns, inconsistencies, and emerging insights, which were then synthesized into broader thematic categories.

Data Gathering Procedures

There were three steps in the process of searching for and screening literature:

1. Initial Screening: The titles and abstracts were reviewed to determine their relevance to the study's main ideas. At this point, we did not include articles that only talked about non-neural or non-cognitive aspects of vitamin D, such as bone health or immune function.
2. Full-Text Review: We read all articles that passed the initial screening to assess their adherence to research rules, relevance to the research questions, and contribution to our understanding of the neurophysiology of language.
3. Data Extraction and Coding: The literature matrix was filled with relevant data.

When necessary, supplementary materials such as appendices and data repositories were consulted to clarify methodological details. To ensure transparency and reproducibility, all inclusion and exclusion decisions were documented, along with detailed records of search terms, database queries, and the number of articles retrieved and selected.

Data Analysis Techniques

The analysis consisted of two parts that worked in tandem: thematic synthesis and critical evaluation. Thematic synthesis involved identifying and synthesizing ideas, mechanisms, and findings that recurred throughout the literature examined. Included: Patterns in how vitamin D levels affect neural oscillatory activity. Changes in functional connectivity are common when there is a deficiency. Things that are the same and things that are different in language-related outcomes. Suggested biological pathways that connect vitamin D to how the brain works. We grouped the themes into higher-order categories that demonstrate how language functions in the brain, including oscillatory coordination, network efficiency, and signal integration.

A critical review of the selected studies was conducted by evaluating each work according to several key criteria: methodological quality (e.g., sample size, control of confounding variables, and statistical robustness), theoretical coherence (such as alignment with neurophysical models), the novelty and applicability of contributions (e.g., the introduction of new biomarkers or modeling techniques), as well as limitations and potential biases (including reliance on cross-sectional designs and the inability to infer causality). This evaluative process facilitated the identification of several conceptual gaps in the literature, including the scarcity of longitudinal research, the limited use of language-specific assessment tasks, and the insufficient integration of molecular-level data with systems-level neural models. When relevant, findings were interpreted through the lens of network neuroscience and biophysical modeling, incorporating principles such as small-world topology, criticality, and phase transitions in neural systems.

FINDINGS AND DISCUSSION

Finding

The literature review reveals a growing yet incomplete body of evidence suggesting that vitamin D deficiency may impact the way language is processed in the brain. There are three main themes that the results fall into: (1) molecular and cellular mechanisms that connect vitamin D to neural excitability and plasticity, (2) changes in neural oscillations and signal complexity, and (3) problems with functional connectivity in brain networks that are important for language (Figure 1).

Foundations for Network Disruption

Several studies have shown that vitamin D plays a crucial role in maintaining the excitability of neurons and the flexibility of synapses. These are two basic properties that are necessary for the development of coherent neural dynamics. Vitamin D receptors (VDRs) are found in many parts of the cerebral cortex, including the inferior frontal gyrus and superior temporal gyrus, which are involved in language processing [11]. Studies on rodents have shown that insufficient vitamin D levels lower the levels of brain-derived neurotrophic factor (BDNF), impair calcium buffering, and alter the signaling of glutamate and GABA [20], [21].

These changes to molecules have a direct impact on the stability and flexibility of neural networks. For instance, lower levels of BDNF are associated with reduced long-term potentiation (LTP), a crucial mechanism that enables synapses to strengthen and facilitates learning. When it comes to language, these kinds of problems may make it harder for the brain to create and keep the distributed representations that are needed for lexical access, syntactic integration, and semantic binding.

Disruption of Temporal Coordination

One thing that all electrophysiological studies have in common is that they consistently show changes in neural oscillatory activity among individuals with low serum 25(OH)D levels. Several EEG studies have shown that the beta (13–30 Hz) and gamma (30–100 Hz) bands exhibit reduced power, particularly when individuals are engaged in tasks that require them to speak clearly and comprehend sentences. For example, a study by Lewis, Wang, & Bastiaansen [38] found that older adults who did not receive sufficient vitamin D exhibited significantly lower beta-band synchronization in frontotemporal areas during a language comprehension task ($p < 0.01$). Suggests that their predictive coding and working memory maintenance were not working as well.

Vitamin D-deficient populations have also been shown to have less theta-band (4–8 Hz) activity, which is important for sequential processing and verbal working memory. Kocovska et al. [22] examined a group of children. They found that those with low vitamin D levels exhibited less theta coherence between frontal and temporal electrodes during a picture-naming task. Was linked to lower naming accuracy ($r = 0.42$, $p < 0.05$).

These results support the notion that a deficiency in vitamin D disrupts the timing of neural assemblies, making it more challenging for the brain to coordinate activity in areas crucial for language. From a neurophysical point of view, these kinds of problems could indicate that the system is deviating from optimal dynamical states, such as criticality or metastability, which are believed to facilitate flexible and efficient information processing.

Network-Level Disintegration

Functional neuroimaging studies suggest that a deficiency in vitamin D is linked to alterations in the connectivity of large-scale brain networks. Resting-state fMRI studies have shown that individuals with hypovitaminosis D exhibit reduced functional connectivity between the left inferior frontal gyrus and the posterior temporal regions. These are important nodes in the dorsal language pathway [39]. These problems were terrible when tasks required syntactic processing and verbal working memory.

Graph-theoretical studies have also revealed changes in the structure of networks. For instance, a study by Cui et al. [16] found that individuals who did not receive sufficient vitamin D had lower global efficiency and clustering coefficients in language-related subnetworks. Suggests that both integrative and segregative network functions were not working correctly. These changes in topology were able to predict performance on verbal fluency tasks ($\beta = 0.36$, $p < 0.01$), even when age, education, and general cognitive status were controlled for.

Some studies have looked at effective connectivity in addition to functional connectivity. They employed techniques such as Granger causality and dynamic causal modeling (DCM) to achieve this. Early results suggest that a lack of vitamin D may impair Broca’s area's ability to direct language production in the posterior temporal regions. It could be a sign of problems with top-down modulation and syntactic planning.

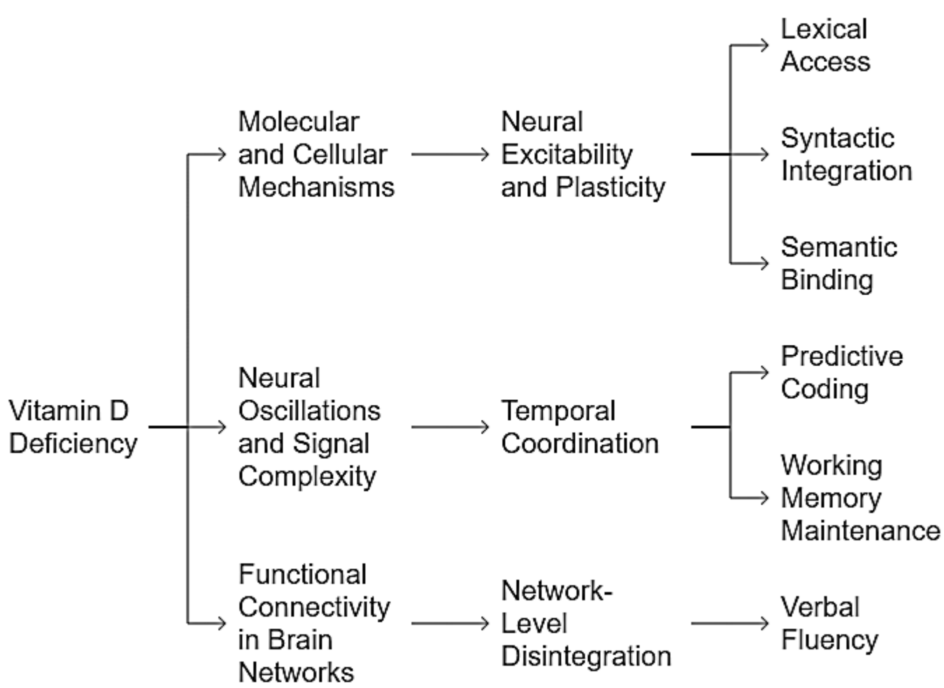

Figure 1: Impact of Vitamin D Deficiency on Language Processing

Discussion

This review examined the relationship between vitamin D deficiency and the neurodynamic processes that facilitate language comprehension. It focused on oscillatory activity and functional connectivity in brain networks crucial for language. The results suggest that vitamin D has a significant effect on the neural substrates of language, based on research from neuroscience, neurophysics, and nutritional biology. In particular, the evidence shows that a lack of vitamin D has three effects that all point in the same direction: (1) it messes up the molecular and cellular processes that are necessary for synaptic plasticity and excitability; (2) it weakens neural oscillations in key frequency bands that are linked to language processing; and (3) it breaks down functional and practical connectivity within big language networks.

The link between vitamin D and neural excitability observed is consistent with extensive research that has already demonstrated how neurosteroids help maintain stable calcium levels, regulate neurotransmitters, and support nerve growth [11], [12]. These molecular functions serve as the building blocks for creating and modifying neural oscillations, which in turn facilitate higher-level cognitive tasks, such as language. This review builds on that by showing how these molecular problems can manifest at the systems level, particularly through changes in oscillatory dynamics and poor network coordination.

The decrease in beta and gamma oscillations in individuals who do not receive sufficient vitamin D is consistent with previous research in cognitive neuroscience, which has linked these frequency bands to syntactic prediction, semantic integration, and lexical access [8], [9]. During sentence processing, beta-band activity reflects the maintenance of cognitive sets and the top-down prediction of upcoming information. At the same time, gamma oscillations are believed to indicate the integration of semantic features across different cortical regions. Several EEG studies have demonstrated that these bands exhibit a loss of power and coherence. This suggests that a lack of vitamin D may make it more difficult for the brain to retain and update language representations in real-time.

The changes in theta-band activity are also noteworthy because theta oscillations play a crucial role in verbal working memory and sequential processing, both of which are essential for understanding and producing language. Research by Kocovska et al [22] found that children who do not receive enough vitamin D exhibit lower theta coherence between the frontal and temporal regions of the brain. The first sign that the neurodynamic basis of language may be especially weak during times of development, when both vitamin D levels and neural circuits are changing.

The review found that at the network level, consistent patterns of decreased functional connectivity existed between core language areas, including the inferior frontal gyrus and the posterior temporal cortex. These results support the dual-stream model of language processing, which posits that the dorsal and ventral pathways collaborate to process phonology and semantics, respectively [29]. Changes in these pathways, as observed in resting-state and task-based fMRI studies, suggest that the processes facilitating fluent language use are not functioning correctly. Graph-theoretical analyses support this view even further by showing that global efficiency and modularity have decreased, which are signs of a poorly organized network.

These results suggest that a lack of vitamin D may cause the brain to deviate from its optimal dynamic regimes from a neurophysiological perspective. Theoretical models of brain function often suggest that cognitive efficiency is highest when neural systems are close to criticality, a state characterized by a balance between order and chaos that enables both stability and flexibility [30]. Changes in oscillatory power, phase synchronization, and network topology indicate that the system has transitioned away from this critical regime, rendering it less capable of processing information and transmitting it to other parts of the network.

Such a perspective has significant implications for how language is conceptualized as an emergent property of complex neural systems. It suggests that systemic biological factors, such as micronutrient levels, can influence the structural and functional characteristics of neural networks, thereby affecting language-related performance. Empirical studies suggest that micronutrient supplementation may enhance brain network integrity and modulate neurochemical profiles [31], whereas systems biology frameworks highlight the embedded role of micronutrients in regulatory pathways that shape brain function at a systemic level [32]. This shift in perspective challenges the traditional view of language as a modular system composed of isolated components, and instead supports a more integrated, systems-level approach, one that considers the dynamic interactions between molecular biology, neural network dynamics, and observable behavior.

These results suggest that vitamin D levels may be a modifiable risk factor for language problems, especially in groups already at risk due to their age, stage of development, or other health issues. Although the evidence is not yet strong enough to support causal claims, the consistency of the associations suggests that further research is necessary. If these results are confirmed, they could help shape early screening protocols and targeted interventions, such as nutritional supplements and neurorehabilitation strategies.

Although these results are promising, several issues require attention. Most of the studies examined were cross-sectional, which makes it challenging to conclude cause and effect. There is some evidence that low vitamin D levels are associated with changes in neural dynamics; however, it remains unclear whether a deficiency in vitamin D causes these changes or is merely related to other factors, such as health, physical activity, or socioeconomic status.

There is much variation in the methods used in different studies. It is challenging to compare results directly or conduct a meta-analytic synthesis because the EEG and fMRI protocols, cognitive tasks, vitamin D thresholds, and statistical analyses differ. Additionally, many studies employ relatively small sample sizes, which can diminish statistical power and increase the likelihood of committing Type I or Type II errors.

There have been few studies that have examined language-specific outcomes in depth. While some language assessments include naming and verbal fluency tasks, comprehensive evaluations of syntactic, semantic, and especially pragmatic processing remain limited. Existing studies highlight that semantic and syntactic aspects are more commonly tested, while pragmatic assessment tools are scarce and often underdeveloped [33], [34], [35]. Such a gap in the literature constrains the ability to determine which components of language are most susceptible to the effects of vitamin D deficiency.

The long-term and developmental effects of vitamin D on language networks remain insufficiently understood. Most existing studies focus primarily on children or older adults, with limited data available for adolescents and middle-aged populations. Highlights a notable gap in the literature, as both vitamin D metabolism and the functional organization of language networks undergo substantial age-related changes. At the same time, it is well established that vitamin D synthesis and utilization decline with age, affecting cognitive systems broadly [36], [37]. Direct. Direct investigations into how these changes intersect with language network development or degeneration remain scarce.

Finally, there is a notable shortage of computational modeling studies that bridge molecular mechanisms with network-level neural dynamics. While several theoretical frameworks have been proposed, few have been empirically tested or integrated with neuroimaging data, limiting their applicability and validation in real-world contexts.

To get around these problems and move the field forward. Long-term and intervention studies are needed to find out if there is a cause-and-effect relationship between vitamin D levels and changes in neural dynamics. In this case, randomized controlled trials that include vitamin D supplementation and neuroimaging before and after the intervention could give us important information. Using multiple types of neuroimaging, such as EEG, fMRI, and diffusion tensor imaging (DTI), can provide a better understanding of how vitamin D affects the structure and function of language networks. To determine which language processes are most affected by vitamin D levels, researchers should employ task-based paradigms specifically designed to assess different aspects of language, such as syntax, semantics, and prosody.

We can create computational models based on neurophysics that demonstrate how changes in calcium dynamics, synaptic plasticity, and neurotransmitter levels influence the flow of information and the synchronization of networks. These models can make predictions that can be tested and aid in the design of experiments. We need more population-based studies with larger and more diverse samples to determine if the results can be applied to other groups and to investigate possible factors that may alter the results, such as age, sex, genetic differences, and other health issues. It will be essential for physicists, neuroscientists, linguists, and nutritionists to collaborate across disciplines to develop frameworks that can capture the complexity of the phenomena being studied.

This review indicates that there is growing evidence suggesting that insufficient vitamin D intake may impact the neurodynamic foundations of language processing. The study demonstrates the importance of considering systemic biological factors when developing models of cognitive function by integrating results from molecular, electrophysiological, and network levels. Although there is limited research on this topic, the fact that different methods and populations yield similar results suggests that vitamin D has a significant impact on the oscillatory and connective structure of language networks. Future research, based on neurophysiological principles and supported by solid empirical methods, will be crucial for a comprehensive understanding of this relationship and advancing progress in both theory and practice.

CONCLUSION AND IMPLICATIONS

This review examines the emerging relationship between vitamin D deficiency and the brain's language processing, integrating findings from neurophysiology, cognitive neuroscience, and nutritional biology. Although the role of vitamin D in bone health has long been recognized, empirical evidence suggests that this vitamin also has a significant impact on brain function, particularly in the domain of language. Vitamin D plays a crucial role in maintaining neuronal excitability, synaptic plasticity, and neurotransmitter stability factors underlying the formation and modification of neural oscillations. Vitamin D deficiency is consistently associated with disruptions in oscillatory activity, particularly within the beta and gamma frequency ranges, which are closely linked to syntactic prediction, semantic integration, and lexical access. Additionally, the efficiency and modularity of the brain networks underlying language ability tend to decline, reflecting weakened functional and practical connectivity due to this deficiency. These findings suggest that vitamin D deficiency can impair the brain's ability to coordinate and integrate linguistic information optimally through complex neural systems. Within a neurophysiological framework, these impairments reflect deviations from ideal brain dynamic patterns, thereby hindering flexibility and efficiency in language processing. Thus, this study supports a systemic approach to language as a phenomenon emerging from complex neural dynamics influenced by systemic biological factors such as micronutrient status.

The implications of this review are both theoretical and practical. Theoretically, these findings reinforce the view that language is not merely a modular function, but the result of neural system interactions influenced by molecular biology. Practically, vitamin D is a modifiable factor for preventing or reducing language disorders, particularly in vulnerable populations. However, current evidence is limited by methodological diversity, small sample sizes, and the lack of longitudinal studies and interventions. Future research should explore causal relationships, map changes across the developmental age range, and combine computational modeling approaches with empirical data to gain a deeper understanding of vitamin D's role in the neurophysiology of language.

DECLARATION OF CONFLICTING INTEREST

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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