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Review Article

The Significant Role of Micronutrients in Early Childhood Development: Linking Iron, Zinc, Iodine and DHA to Body–Brain–Behavior Outcomes

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Abstract

Early childhood is a critical developmental period characterized by rapid physical growth, accelerated brain maturation, and the establishment of cognitive and behavioral functions. Adequate nutrition during this period provides the foundation for optimal development by supplying essential nutrients required for cellular growth, neurological organization, immune function, and metabolic regulation. While macronutrients provide energy and structural components, micronutrients serve as biological regulators that influence multiple developmental pathways. Deficiencies of key micronutrients during early life may compromise physical growth, impair neurodevelopment, and negatively influence learning ability, emotional regulation, and behavioral outcomes. The Body–Brain–Behavior (3B) Axis provides an integrated framework for understanding how nutrition influences whole-child development. This approach recognizes that physical growth, brain maturation, and behavioral regulation are interconnected processes driven by common nutritional and biological pathways. Among essential micronutrients, iron, zinc, iodine, and docosahexaenoic acid (DHA) have emerged as critical contributors to early childhood development. Iron supports oxygen transport, mitochondrial energy production, DNA synthesis, myelination, and neurotransmitter metabolism, particularly dopamine pathways involved in attention, motivation, and learning. Zinc plays essential roles in cellular growth, immune regulation, neuronal communication, synaptic formation, and neuroplasticity. Iodine is required for thyroid hormone production, which regulates neuronal migration, brain growth, myelination, and synaptic development. DHA, a long-chain omega-3 fatty acid and major structural component of neuronal membranes, contributes to synapse formation, neural connectivity, visual development, memory, and cognitive function. Importantly, micronutrients do not act independently; rather, they function synergistically through interconnected biological pathways. Adequate availability of multiple micronutrients supports healthy growth, optimal brain architecture, and adaptive behavioral development, whereas deficiencies may create cascading effects across the Body–Brain–Behavior domains. This review discusses the biological mechanisms through which iron, zinc, iodine, and DHA influence early childhood development and highlights their importance in supporting physical growth, neurodevelopment, cognitive performance, and behavioral regulation. Understanding these relationships reinforces the importance of micronutrient-focused nutritional strategies during the first years of life to maximize developmental potential and support lifelong health outcomes.

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Keywords

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1. Introduction

Early childhood represents one of the most dynamic periods of human development, during which biological systems undergo rapid transformation. Growth of body tissues, maturation of the immune system, development of neural networks, and emergence of cognitive and behavioral abilities occur simultaneously during this period. The nutritional environment during early life therefore plays a fundamental role in determining developmental outcomes [1].

Historically, child health assessment has primarily focused on physical indicators such as weight, height, and growth velocity. Although these measurements remain important, they provide only a partial understanding of developmental progress. Modern nutritional science recognizes that optimal development extends beyond physical growth and includes cognitive capacity, emotional regulation, attention, learning ability, and social interaction [2].

The Body–Brain–Behavior (3B) framework emphasizes that child development occurs through the interaction of three interconnected domains:

Table 1. Body–Brain–Behavior (3B) framework.

Domain	Biological Focus	Developmental Outcomes
Body	Growth, immunity, bone formation, energy metabolism	Physical health and resilience
Brain	Neurogenesis, synapse formation, myelination, neural connectivity	Learning, memory, cognition
Behavior	Neurotransmitter balance, emotional regulation, social interaction	Attention, mood, adaptive behavior

Nutrition represents the common biological input connecting these three domains. A nutritional deficiency rarely affects only one system because many micronutrients participate simultaneously in growth, neurological function, and behavioral regulation [3].

The first 1,000 days, beginning from conception through the first two years of life, represent a particularly important period because the brain undergoes rapid structural and functional development. During this stage, nutrients such as iron, zinc, iodine, and DHA are required for processes including neuronal differentiation, synapse formation, myelination, and neurotransmitter synthesis. Micronutrient deficiencies remain a significant global challenge, particularly among vulnerable populations. Evidence suggests that inadequate micronutrient availability during early development may influence not only immediate health outcomes but also long-term cognitive and behavioral trajectories. This review explores the significant role of iron, zinc, iodine, and DHA in early childhood development and examines how these micronutrients influence Body–Brain–Behavior outcomes through biological mechanisms [4].

2. The Body–Brain–Behavior Axis: A Nutritional Framework for Development

The Body–Brain–Behavior Axis describes the interconnected biological relationship between nutritional status, physiological development, neurological maturation, and behavioral outcomes.

Table 2. Micronutrients Across Body–Brain–Behavior Domains [5].

Micronutrient	Body Effects	Brain Effects	Behavioral Effects
Iron	Oxygen transport, energy metabolism, immunity	Myelination, neurotransmitter synthesis, cognition	Attention, motivation, learning
Zinc	Growth, immune function, tissue development	Synaptic formation, neuronal signaling	Emotional regulation
Iodine	Thyroid hormone synthesis	Brain maturation and neural development	Cognitive performance
DHA	Cell membrane development	Synapse formation, neural connectivity	Memory and attention

The integrated framework highlights that growth is not complete when physical parameters alone improve. Optimal development requires coordinated progress across physical, neurological, and behavioral domains.

3. Biological Mechanisms Linking Micronutrients with Body–Brain–Behavior Outcomes

Micronutrients influence early childhood development through multiple biological pathways involving cellular growth, energy metabolism, neurological maturation, neurotransmitter regulation, and hormonal control. During early life, the developing brain requires continuous availability of essential nutrients to support neurogenesis, synaptic formation, myelination, and functional connectivity. Deficiencies during this critical period may interfere with both structural brain development and behavioral outcomes [6].

3.1. Iron: A Key Regulator of Brain Energy, Myelination, and Cognitive Function

Iron is one of the most important micronutrients required for early childhood development. Although traditionally recognized for its role in hemoglobin formation and oxygen transport, iron also performs several critical neurological functions [7].

Iron supports oxygen transport by ensuring adequate oxygen delivery to rapidly developing tissues, including the brain. It is also essential for mitochondrial energy production, which enables cellular energy generation and supports neuronal metabolism. In addition, iron contributes to myelination, promoting the formation of myelin that improves communication between neurons. Iron also plays an important role in neurotransmitter synthesis by participating in dopamine, serotonin, and norepinephrine pathways.

The developing brain has high metabolic demands, making sufficient iron availability essential for optimal neuronal function. Iron contributes to hippocampal development, myelin formation, and neurotransmitter regulation [8].

Early-life iron deficiency may negatively influence attention and concentration, learning ability, memory development, psychomotor development, and emotional and behavioral regulation. Iron deficiency during infancy has been associated with altered cognitive and behavioral outcomes, highlighting the importance of maintaining adequate iron status during critical periods of brain development [9].

3.2. Zinc: Supporting Growth, Immunity, and Neural Development

Zinc is an essential trace element involved in cellular growth, immune function, and neurological development. It is highly concentrated in brain regions associated with learning and memory, including the hippocampus and cerebral cortex [10].

Zinc contributes to DNA synthesis, cell division, protein synthesis, immune regulation, neuronal communication, synaptic formation, and neural plasticity. During brain development, zinc supports neuronal differentiation, neuronal migration, synapse formation, and neurotransmitter regulation.

Zinc deficiency during early life may affect physical growth, immune resilience, cognitive development, and emotional regulation. Experimental and clinical evidence demonstrates that zinc plays an important role in maintaining normal central nervous system development [11].

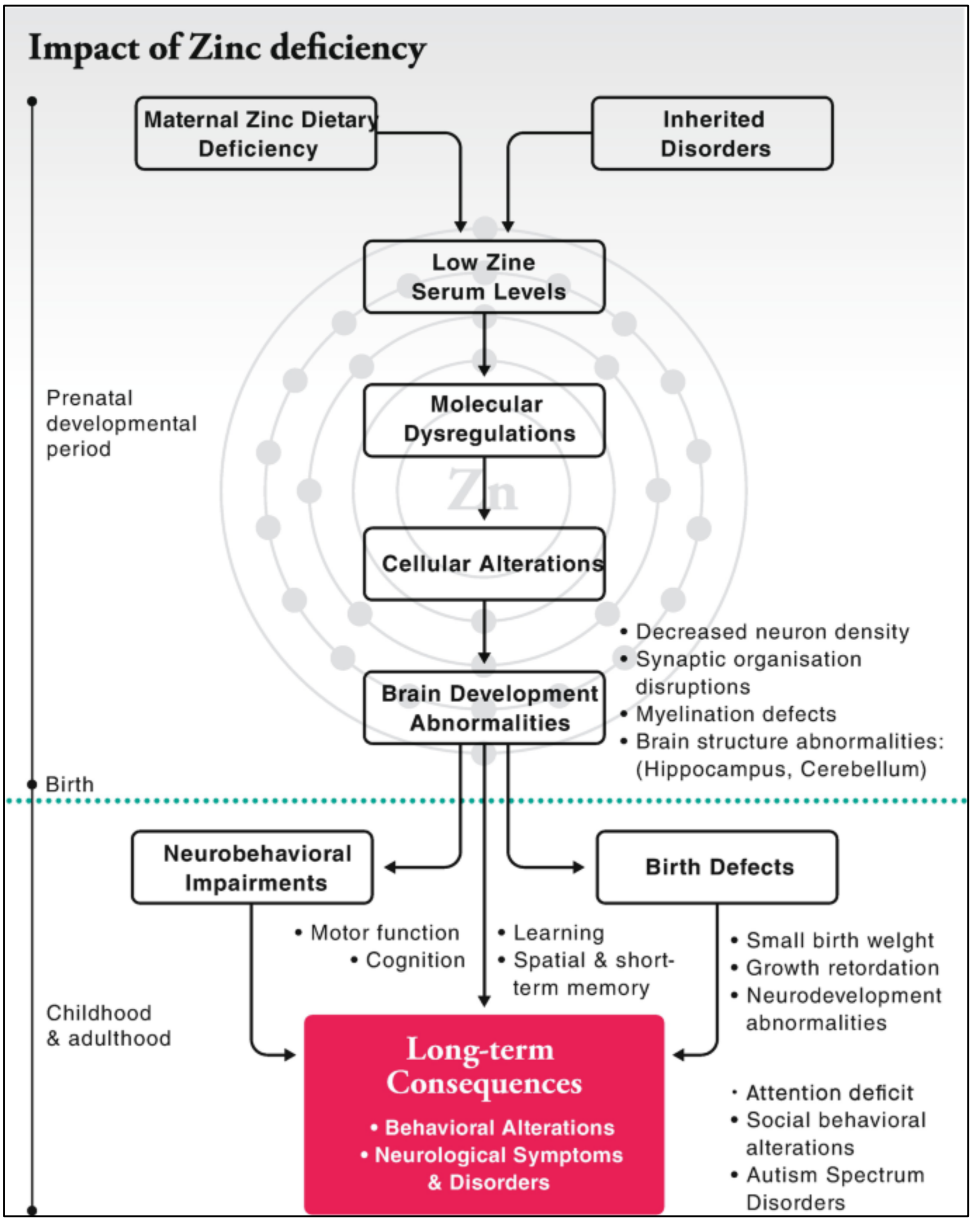

Figure 1. *Impact of Zinc Deficiency with Long-term Consequences [12].*

3.3. Iodine: The Thyroid–Brain Development Connection

Iodine plays a fundamental role in early childhood development through its essential role in thyroid hormone synthesis. Thyroid hormones regulate several developmental processes that are crucial for brain maturation [13].

Iodine supports thyroid hormone production, which regulates neuronal migration, promotes myelination, supports synaptic development, and influences overall brain growth and maturation. Thyroid hormones are particularly important during fetal life and early childhood, as the nervous system undergoes rapid structural organization during these critical developmental periods [14].

Inadequate iodine status may negatively affect cognitive development, learning capacity, neurological maturation, and intellectual potential. Evidence indicates that iodine deficiency can impair neurodevelopment because thyroid hormones serve as key regulators of neuronal growth, differentiation, and brain development [15].

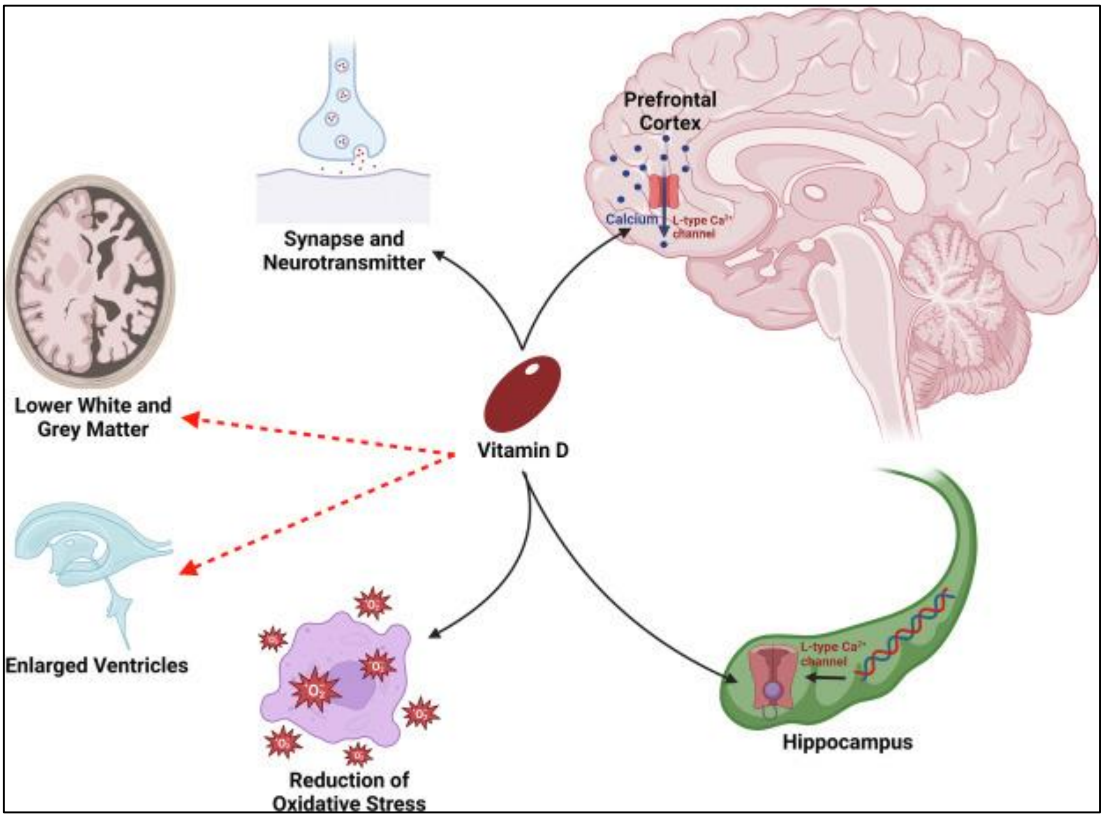

Figure 2. Vitamins, minerals and their maternal levels' role in brain development [16].

3.4. DHA: A Structural Foundation for Brain Development

Docosahexaenoic acid (DHA) is a long-chain omega-3 fatty acid that serves as an important structural component of neuronal membranes. The developing brain accumulates significant amounts of DHA during early childhood, highlighting its essential role in neural growth and function [17].

DHA supports neuronal membrane structure by enhancing membrane fluidity, facilitating neural signaling, promoting synaptic development, and supporting visual maturation. It also influences pathways involved in learning and memory. Through these functions, DHA contributes to the formation and maintenance of neural networks responsible for cognition, attention, and memory processes [18].

Adequate DHA availability during early childhood supports brain connectivity, learning readiness, memory formation, cognitive performance, and visual development. Recent evidence continues to explore the role of DHA supplementation in neurodevelopment, suggesting that DHA is biologically important for brain development, although outcomes may vary depending on nutritional status, timing of intake, and population characteristics [19].

3.5. Nutrient Synergy: Why Multiple Micronutrients Matter

Child development depends on the combined effects of multiple nutrients rather than isolated micronutrients. The biological pathways involved in growth and neurodevelopment are interconnected, meaning that deficiencies often occur together and influence overlapping systems [20].

Together, these nutrients create a supportive biological environment required for optimal development across the Body–Brain–Behavior domains [21].

Table 3. Nutrient Synergy in Body–Brain–Behavior Development.

Micronutrient	Primary Biological Contribution
Iron	Oxygen transport, energy metabolism, neurotransmitter synthesis
Zinc	Growth, immunity, neuronal signaling, synaptic function
Iodine	Thyroid hormone production and brain maturation

Micronutrient	Primary Biological Contribution
DHA	Neuronal membrane structure, connectivity, cognition
B-vitamins	Energy metabolism and neurological function
Vitamin D	Bone development, immunity, cellular signaling
Magnesium	Neural regulation and stress response

4. Applying the Body–Brain–Behavior Approach in Practical Experience

The Body–Brain–Behavior framework provides healthcare professionals with a broader perspective for evaluating child development. Nutritional assessment should extend beyond physical growth indicators and include developmental milestones, cognitive function, and behavioral outcomes [22].

Table 4. *Clinical Application of the 3B Framework [23, 24].*

Domain	Clinical Focus	Nutritional Consideration
Body	Growth, immunity, physical development	Protein, iron, zinc, calcium, vitamin D
Brain	Learning, memory, neurodevelopment	DHA, iron, iodine, zinc, B-vitamins
Behavior	Attention, mood, social interaction	Iron, DHA, zinc, magnesium

A comprehensive approach allows healthcare professionals to identify nutritional risks earlier and provide targeted nutritional guidance [25, 26].

Child development depends on the combined effects of multiple nutrients rather than isolated micronutrients.

5. Conclusion

Micronutrients are essential biological regulators that shape early childhood development by influencing physical growth, brain maturation, and behavioral regulation. The evidence highlights that iron, zinc, iodine, and DHA play distinct yet interconnected roles across the Body–Brain–Behavior Axis, supporting processes such as cellular growth, immune function, neurotransmitter regulation, synaptic development, myelination, and cognitive performance. Adequate micronutrient availability during early life, particularly throughout the first 1,000 days, provides the foundation for healthy growth trajectories and optimal developmental outcomes. Evidence from systematic reviews indicates that early-life micronutrient interventions can improve nutrient status, particularly iron and zinc status, although effects on broader developmental outcomes may vary depending on timing, population characteristics, and nutritional context. A comprehensive nutritional approach that considers multiple micronutrients rather than isolated nutrients is essential because childhood development depends on coordinated biological pathways [27, 28]. Iron supports oxygen delivery and neurotransmitter metabolism, zinc contributes to growth and neuronal signaling, iodine enables thyroid-mediated brain maturation, and DHA supports neuronal structure and connectivity. Together, these nutrients contribute to healthy physical growth, improved brain development, enhanced learning and memory, attention regulation, and emotional wellbeing. The Body–Brain–Behavior framework provides a practical and holistic approach for healthcare professionals to understand and communicate the importance of early-life nutrition. By integrating nutritional assessment with growth monitoring, developmental evaluation, and behavioral observation, healthcare providers can better identify nutritional risks and support individualized strategies to optimize child development. Ultimately, ensuring adequate intake of essential micronutrients during early childhood represents an important investment in lifelong health, cognitive potential, and overall wellbeing.

Author Contributions

Mohammad Mahmudul Hasan: Conceptualization, Formal Analysis, Investigation, Methodology, Project administration, Supervision, Validation, Writing – original draft, Writing – review & editing

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Mohammad Shaheb Ali: Conceptualization, Data curation, Formal Analysis, Investigation, Validation, Visualization, Writing – original draft

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Biswajit Chowdhury: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration

Conflicts of Interest

The authors declare no conflicts of interest.

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