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Review Article

The Science Behind the Body-Brain-Behavior Axis: How Early-Life Nutrition and Micronutrients Shape Neurodevelopment and Behavioral Regulation of Children

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Abstract

Early childhood represents a critical developmental period during which nutrition provides the biological foundation for physical growth, brain maturation, cognitive development, and behavioral regulation. The traditional assessment of child development has largely focused on physical indicators such as weight and height; however, emerging scientific evidence emphasizes that complete growth requires a multidimensional approach integrating Body, Brain, and Behavior (3B) outcomes. The Body-Brain-Behavior Axis describes the interconnected relationship between nutritional intake, physiological growth, neurodevelopmental processes, and behavioral outcomes, highlighting nutrition as a fundamental regulator of lifelong health trajectories. During early life, rapid cellular proliferation, synapse formation, myelination, neurotransmitter synthesis, and immune development create a high demand for essential nutrients. Micronutrients including iron, zinc, iodine, DHA, B-vitamins, vitamin D, calcium, and magnesium act through multiple biological pathways to support these processes. Iron contributes to oxygen transport, energy metabolism, neurotransmitter synthesis, and myelination; iodine supports thyroid hormone production and neurological development; zinc regulates neuronal signaling, immune function, and synaptic plasticity; while DHA plays a critical role in neuronal membrane formation, synapse development, and cognitive function. B-vitamins participate in energy metabolism and neurotransmitter pathways, whereas vitamin D, calcium, and magnesium contribute to skeletal development, cellular signaling, and neurological regulation. The relationship between nutrition and development is bidirectional. Nutritional inadequacy can impair growth, reduce neuroplasticity, disrupt neurotransmitter balance, and influence emotional regulation, attention, learning ability, and social interaction. Conversely, adequate nutrient intake during critical developmental windows, particularly the first 1,000 days of life, supports optimal body growth, brain architecture, and behavioral competence. Nutrient deficiencies rarely affect a single developmental domain; rather, they create interconnected consequences across physical, cognitive, and emotional systems. This review explores the scientific mechanisms underlying the Body-Brain-Behavior Axis and examines how early-life nutrition and micronutrients influence neurodevelopment and behavioral regulation. Understanding these biological connections provides an integrated framework for healthcare professionals to promote holistic child development through evidence-based nutritional strategies.

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1. Introduction

Early childhood is a period of extraordinary biological transformation characterized by rapid growth, brain development, immune maturation, and the establishment of behavioral patterns. During this period, nutritional requirements increase substantially to support cellular expansion, tissue development, and neurological processes. Adequate nutrition is therefore essential not only for preventing growth failure but also for supporting cognitive abilities, emotional regulation, learning capacity, and social development [1].

Historically, child growth monitoring has emphasized anthropometric indicators such as weight, height, and body mass index. Although these measurements remain important clinical indicators, they represent only one dimension of development. A child's developmental potential depends on the coordinated maturation of multiple biological systems, including physical growth, brain development, and behavioral adaptation.

The Body-Brain-Behavior (3B) framework proposed in this review provides an integrated perspective by recognizing that nutrition influences three interconnected developmental domains. The Body domain represents physical growth, immunity, bone development, muscle formation, and energy metabolism. The Brain domain includes neurogenesis, synapse formation, myelination, memory, learning, and cognitive function. The Behavior domain encompasses attention, emotional regulation, motivation, social interaction, and adaptive responses [2].

Although the individual relationships between nutrition, physical growth, neurodevelopment, and behavior are well established in the literature, the Body-Brain-Behavior framework represents an integrative conceptual model developed by the authors to organize these interconnected processes. This framework emphasizes that child development cannot be fully assessed through physical growth parameters alone, as nutrition influences multiple biological systems simultaneously. The first 1,000 days, from conception to approximately two years of age, represent a particularly important nutritional window. During this period, brain development depends on adequate availability of essential nutrients required for synaptic development, myelination, neurotransmitter synthesis, and neuronal connectivity. DHA, iron, and iodine contribute significantly to early brain development, while energy and protein availability remain essential for physical growth [3].

Micronutrient deficiencies during early childhood remain a major global health challenge. Deficiencies in iron, zinc, iodine, and other essential nutrients may compromise physical development and interfere with cognitive and behavioral outcomes. The consequences may extend beyond immediate health effects, potentially influencing educational achievement, productivity, and long-term wellbeing [4]. Therefore, understanding the biological connections between nutrition, brain development, and behavior is essential for developing comprehensive pediatric nutrition strategies. This review examines the scientific mechanisms through which early-life nutrition and micronutrients influence neurodevelopmental and behavioral outcomes within the proposed Body-Brain-Behavior framework [5, 6].

2. The Body-Brain-Behavior Axis: An Integrated Developmental Framework

The *Body-Brain-Behavior (3B) framework proposed in this review* is a conceptual model that integrates established biological relationships between nutrition, physical growth, neurodevelopment, and behavioral outcomes. Although the individual interactions between nutrition and body growth, brain maturation, and behavioral regulation are well supported in the scientific literature, the term "Body-Brain-Behavior Axis" is introduced here as an integrative framework to organize these interconnected developmental domains into a unified perspective [7, 8]. This framework emphasizes that optimal child development cannot be evaluated through physical growth parameters alone but requires consideration of coordinated changes in the body, brain, and behavior.

The novelty of the 3B framework lies in its holistic approach, which highlights nutrition as a common biological determinant influencing multiple developmental systems simultaneously. Rather than viewing nutrients only in relation to isolated deficiencies or single outcomes, this framework emphasizes the interconnected effects of nutrients on growth, neural development, cognitive function, and behavioral regulation.

Table 1. The Body-Brain-Behavior Framework.

Developmental Domain	Major Biological Functions	Key Nutritional Requirements	Developmental Outcomes
Body	Growth, immunity, bone formation, muscle development, and energy metabolism	Protein, zinc, iron, calcium, vitamin D, vitamin C	Healthy growth, physical strength, and immune protection
Brain	Neurogenesis, synapse formation, myelination, neurotransmitter production, and neural connectivity	DHA, iron, iodine, zinc, vitamin B12, folate	Learning, memory, attention, and cognitive development
Behavior	Mood regulation, motivation, social interaction, emotional control, and adaptive responses	Iron, zinc, DHA, B-vitamins, magnesium	Emotional stability, concentration, and adaptive behavior

Nutrition influences these three developmental domains through shared biological pathways. A deficiency of a single nutrient may affect multiple systems because many micronutrients participate in overlapping physiological processes. For example, iron deficiency can reduce oxygen delivery, impair mitochondrial energy production, alter neurotransmitter metabolism, and affect cognitive performance. Zinc deficiency can influence immune function, growth regulation, and neuronal signaling. DHA inadequacy may affect neuronal membrane structure, synaptic communication, learning, and memory.

The interconnected nature of these pathways explains why nutritional inadequacy rarely produces isolated developmental effects. Instead, deficiencies may contribute to a cascade of consequences involving impaired physical growth, altered brain development, and behavioral challenges. Therefore, the 3B framework provides an integrated approach for understanding how early-life nutrition influences multiple aspects of child development while recognizing that these relationships involve complex biological interactions rather than simple linear pathways.

3. Biological Mechanisms Linking Early-Life Nutrition with the Body-Brain-Behavior Axis

Early-life nutrition influences development through multiple interconnected biological pathways involving cellular growth signaling, hormonal regulation, neuronal maturation, neurotransmitter activity, and immune function. Adequate availability of macronutrients and micronutrients provides the molecular signals required for growth, brain plasticity, and behavioral adaptation [9].

3.1. Nutritional Signaling and Cellular Growth: The mTORC1 Pathway

One of the fundamental mechanisms through which nutrition regulates growth is the *mechanistic target of rapamycin complex 1 (mTORC1)* pathway. mTORC1 acts as a central nutrient-sensitive regulator involved in protein synthesis, cellular growth, metabolism, and tissue development [10].

Nutritional availability, particularly amino acids such as *leucine*, activates mTORC1 signaling through Ragulator-Rag GTPase pathways. Growth-related hormones, including insulin and insulin-like growth factor-1 (IGF-1), can also activate PI3K-AKT signaling, which interacts with mTORC1 pathways to regulate cellular growth processes [11].

However, the relationship between nutrition and mTORC1 activity is complex and depends on nutrient availability, developmental stage, and tissue-specific regulation. Experimental studies demonstrate that mTORC1 is an important mediator of nutrient sensing and growth regulation, while evidence from human studies suggests that alterations in nutrient status may influence these pathways and contribute to developmental outcomes.

Table 2. Nutritional Regulation of mTORC1 and Development.

Nutritional Signal	Molecular Pathway	Biological Effect
Amino acids (especially leucine)	Ragulator-Rag GTPase activation	Regulation of protein synthesis and cellular growth
Insulin/IGF-1	PI3K-AKT pathway	Growth stimulation and metabolic regulation
Adequate nutrition	mTORC1 activation	Supports tissue development, cellular repair, and growth

Nutritional Signal	Molecular Pathway	Biological Effect
Nutritional deficiency	Reduced mTORC1 activity	May contribute to impaired growth and altered developmental processes

When nutrition is adequate, mTORC1 promotes anabolic processes including protein synthesis and tissue development. Conversely, nutritional insufficiency may reduce mTORC1 activity, potentially affecting cellular growth and neurodevelopment. However, these effects are influenced by multiple biological factors, and direct clinical outcomes in children require further investigation.

3.2. GH-IGF-1 Axis: Connecting Nutrition with Physical and Neural Growth

The *growth hormone (GH)-IGF-1 axis* is an important endocrine pathway influenced by nutritional status. Adequate energy and protein availability support GH-mediated IGF-1 production, which contributes to growth regulation and tissue development [12].

Nutrition → IGF-1 production → Growth-related signaling → Tissue development

IGF-1 contributes to skeletal growth through chondrocyte proliferation, muscle development through protein synthesis, cellular metabolism, and neurodevelopmental processes including neuronal growth and synaptic maturation.

During early childhood, IGF-1 may support brain maturation by influencing neuronal development, synaptic organization, and myelination. However, the relationship between IGF-1 levels and developmental outcomes is influenced by multiple factors, including genetics, hormonal regulation, and overall nutritional status.

Table 3. *GH-IGF-1 Axis and 3B Outcomes.*

System	Biological Role of IGF-1	Developmental Outcome
Body	Bone growth and muscle protein synthesis	Physical growth and strength
Brain	Neuronal growth and synaptic maturation	Cognitive development
Behavior	Supports neural function and regulation	May influence learning readiness

Nutritional deficiencies may reduce IGF-1 activity and are associated with impaired physical growth and altered developmental outcomes. However, evidence does not suggest a simple linear relationship, as multiple biological and environmental factors contribute to child development.

3.3. Nutrition, Neuroplasticity, and Brain Development

The developing brain undergoes rapid structural and functional changes during early life, including neuron formation, synapse creation, synaptic pruning, myelination, neurotransmitter synthesis, and neural network organization.

These processes require adequate availability of essential nutrients. DHA contributes to neuronal membrane structure, iron supports oxygen metabolism and neurotransmitter pathways, iodine supports thyroid hormone-dependent brain maturation, zinc participates in synaptic signaling, and B-vitamins contribute to cellular energy metabolism.

Adequate nutrition supports neuroplasticity, the ability of the brain to adapt, learn, and form new connections. However, the extent to which improving nutritional intake enhances neurodevelopmental outcomes depends on baseline nutritional status, timing of intervention, and the presence or absence of deficiency [13].

3.4. Neurotransmitter Regulation and Behavioral Development

Behavioral regulation involves complex interactions between neurotransmitter systems, brain development, environmental factors, and individual characteristics. Nutrients contribute to neurotransmitter synthesis, neuronal communication, and regulation of neural pathways.

Iron is involved in dopamine metabolism and myelination, zinc contributes to neuronal communication and synaptic function, DHA supports neuronal membrane function, B-vitamins participate in neurotransmitter-related metabolic pathways, and magnesium contributes to neural signaling regulation.

Dopamine contributes to motivation, reward processing, attention, and learning behavior, while serotonin contributes to mood regulation and emotional stability. Oxytocin is involved in social bonding and interpersonal interaction.

Although biological mechanisms support a role for nutrition in neurotransmitter regulation, evidence from human studies is variable. Nutritional inadequacy may be associated with difficulties in attention, emotional regulation, and social behavior, but causal relationships depend on the specific nutrient, severity of deficiency, and developmental context.

3.5. The HPA Axis, Stress Regulation, and Nutrition

The *hypothalamic-pituitary-adrenal (HPA) axis* regulates physiological responses to stress through hormonal signaling involving cortisol regulation.

Nutritional status may influence stress-response pathways through complex interactions involving metabolism, inflammation, hormonal regulation, and brain development.

Nutritional inadequacy → Altered metabolic and hormonal regulation → Possible changes in HPA axis activity → Potential effects on stress-related outcomes

Chronic alterations in stress hormone regulation may influence memory formation, emotional regulation, learning ability, and social behavior. However, current evidence primarily demonstrates associations, and further research is needed to clarify causal relationships between early-life nutrition, HPA axis regulation, and developmental outcomes [14].

4. Micronutrients Shaping Neurodevelopment and Behavioral Regulation

Evidence regarding micronutrients and child development comes from different types of studies, including investigations of nutrient deficiency, observational studies examining nutritional status and developmental outcomes, and supplementation trials evaluating the effects of additional nutrient intake. These forms of evidence provide different levels of support. While deficiency studies strongly demonstrate the importance of adequate nutrient availability for normal development, supplementation studies in already well-nourished children have shown more variable effects. Therefore, the developmental benefits of micronutrients should be interpreted according to nutritional status, dose, timing, and individual needs. Micronutrients are required in small amounts but have powerful biological effects. They participate in enzymatic reactions, hormone synthesis, neurotransmitter pathways, immune regulation, and brain development.

***Table 4.** Key Micronutrients and Their Role in Body-Brain-Behavior Outcomes [15].*

Micronutrient	Role in Body	Role in Brain	Role in Behavior
Iron	Oxygen transport, energy metabolism, immunity	Myelination, dopamine synthesis, cognitive development	Attention, learning, emotional regulation
Zinc	Growth, immune function, tissue repair	Synaptic plasticity and neuronal signaling	Mood regulation and behavior
Iodine	Thyroid hormone production	Brain maturation and neurological development	Cognitive performance
DHA/Omega-3	Cell membrane function	Synapse formation, neural connectivity, memory	Attention and emotional regulation
B-vitamins	Energy metabolism	Neurotransmitter synthesis and brain function	Mood and cognitive performance
Vitamin D	Bone health and immunity	Neurodevelopmental signaling	Emotional balance
Calcium	Bone mineralization	Neural signaling	Neuromuscular function
Magnesium	Cellular metabolism	Neural transmission	Stress regulation

4.1. Iron: Supporting Cognitive Development and Behavioral Regulation [16]

Iron is essential for early brain development and plays important roles in oxygen delivery to developing tissues, mitochondrial energy production, myelin formation, and dopamine metabolism. Iron deficiency may negatively affect attention and concentration, memory and learning ability, psychomotor development, and behavioral regulation.

4.2. Zinc: Growth, Immunity, and Neurodevelopment

Zinc supports both physical growth and brain function through its involvement in DNA synthesis and cell division, immune function, neuronal communication, and synapse formation and plasticity. Zinc deficiency may therefore impair growth and immunity, cognitive development, and emotional regulation.

4.3. Iodine: Essential for Brain Maturation

Iodine supports thyroid hormone production, which is critical for normal brain development. It contributes to brain growth, neuronal migration, myelination, and synaptic development. Adequate iodine intake therefore supports optimal cognitive development and healthy neurological function.

4.4. DHA: Structural Foundation of the Developing Brain [17]

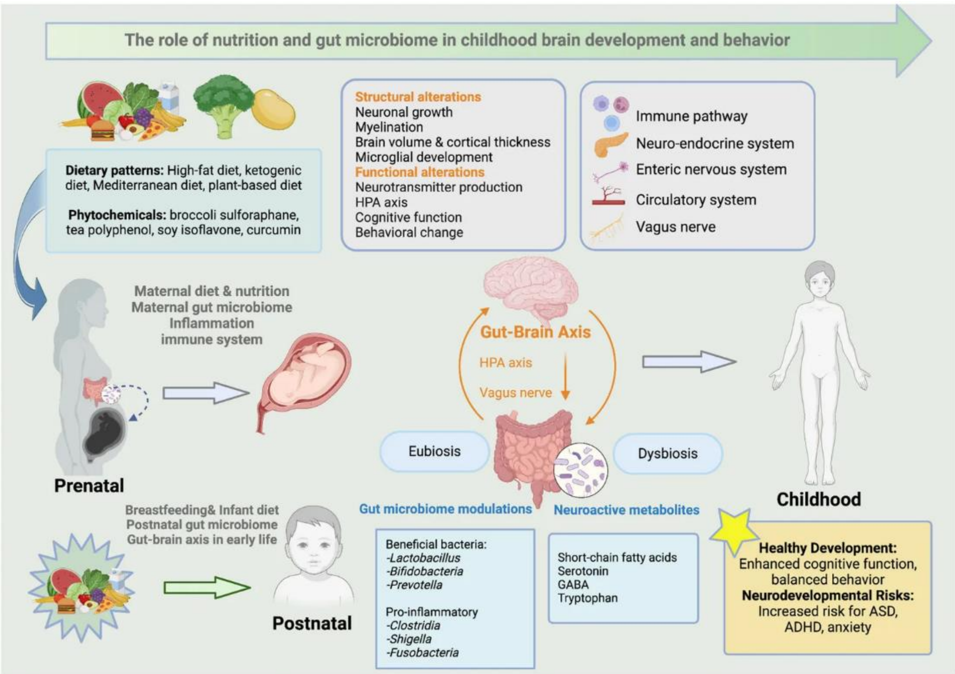
DHA is a major structural component of neuronal membranes and plays important roles in synapse formation, membrane flexibility, neural signaling, visual development, learning, and memory. The high requirement for DHA during early life reflects the rapid development of brain networks and its contribution to cognitive function.

Together, iron, zinc, iodine, and DHA contribute to optimal *Body-Brain-Behavior* development by supporting interconnected aspects of physical growth, neurological maturation, cognitive function, and behavioral development.

5. Practical Framework for Healthcare Professionals [18]

The Body-Brain-Behavior Axis provides a practical framework for healthcare professionals to evaluate child development beyond conventional measures of weight and height. A child's nutritional status influences multiple interconnected systems, and therefore assessment should include physical growth, developmental milestones, cognitive function, and behavioral wellbeing.

The clinical focus should shift from preventing nutrient deficiency alone toward *optimizing developmental potential* through adequate nutrient intake during critical growth periods [19].



Key considerations for healthcare professionals include:

Figure 1. *The role of nutrition and gut microbiome in childhood brain development and behavior [20].*

5.1. Early Nutritional Assessment [21]

Routine pediatric assessment should consider growth parameters and physical development, dietary diversity and nutrient density, micronutrient adequacy, cognitive milestones, and behavioral indicators including attention, emotional regulation, and social interaction. The 3B approach emphasizes that evaluating only physical growth may overlook important aspects of development because nutrition influences body, brain, and behavior simultaneously.

5.2. Promoting Nutrient-Dense Early-Life Nutrition [22]

Complementary feeding after six months should provide adequate energy, protein, essential fatty acids, vitamins, and minerals. The nutritional framework highlights that food should be nutrient-dense, age-appropriate, and provided through responsive feeding practices. When dietary gaps exist, fortified foods or supplementation strategies may be considered based on clinical needs.

5.3. Moving Toward a Multi-Nutrient Perspective [23]

Child development does not depend on a single nutrient; rather, multiple micronutrients work together through overlapping biological pathways. Iron supports oxygen delivery, neurotransmitter metabolism, and cognitive function, while zinc contributes to growth, immune function, and neuronal signaling. Iodine plays a critical role in thyroid hormone-mediated brain development, and DHA supports neuronal membrane formation, synaptic development, and learning processes. Therefore, healthcare professionals should adopt a holistic nutritional perspective that considers the combined role of multiple nutrients rather than focusing exclusively on individual nutrient deficiencies.

6. Conclusion

The Body-Brain-Behavior Axis provides a comprehensive scientific framework explaining how early-life nutrition shapes childhood development. Nutrition serves as a fundamental biological signal connecting physical growth, brain maturation, and behavioral regulation. Early childhood, particularly the first 1,000 days, represents a critical developmental window when nutritional inputs influence cellular growth pathways, hormonal regulation, neural connectivity, and cognitive function. Micronutrients including iron, zinc, iodine, DHA, B-vitamins, vitamin D, calcium, and magnesium play essential roles across multiple developmental domains. Their effects extend beyond preventing deficiency by supporting neuroplasticity, neurotransmitter balance, learning ability, memory formation, emotional regulation, and social development [24]. The evidence demonstrates that growth is multidimensional. A child may achieve adequate physical growth while still experiencing developmental challenges related to cognition or behavior if nutritional needs are not fully met.

By incorporating the Body-Brain-Behavior framework into pediatric nutrition practice, healthcare professionals can better identify nutritional risks, provide targeted counselling, and support children in achieving their full developmental potential [25].

Future research directions:

Future studies should further explore the long-term impact of DHA status and supplementation during toddlerhood by using well-designed longitudinal studies that follow children across different stages of development. Research should focus on identifying which populations are most likely to benefit from DHA supplementation, considering factors such as baseline dietary intake, genetic variability, nutritional status, and environmental influences. More standardized clinical trials are needed to clarify optimal DHA doses, timing, and duration of supplementation, as well as to better understand its effects on specific cognitive, behavioral, and immune outcomes. Additionally, future investigations should integrate nutritional, neurodevelopmental, and immunological approaches to provide a more comprehensive understanding of how DHA contributes to early-life growth and development. Such evidence will help establish more personalized and evidence-based recommendations for DHA intake during toddlerhood.

Author Contributions

Ilham Imam: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration. Supervision, Validation, Visualization, Writing – original draft

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Conflicts of Interest

The authors declare no conflicts of interest.

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