



Research Article

Human Milk Oligosaccharides (HMOs) in Infant Neurodevelopment: Evidence Linking Gut–brain Signaling to Cognitive Outcomes

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Abstract

This narrative review summarizes current evidence on the association between human milk oligosaccharides (HMOs) and infant neurodevelopment. HMOs are complex bioactive carbohydrates naturally present in human breast milk and are increasingly recognized for their potential role in supporting early brain development through interactions with the gut microbiome, immune system, and metabolic pathways. Relevant literature was identified through structured searches of PubMed, Scopus, and Web of Science covering studies published between 2000 and 2025. The review included human observational cohort studies, mechanistic research, and preclinical models that examined neurodevelopmental outcomes such as cognitive function, language acquisition, motor skills, and socio-emotional development in infants and young children. Current human evidence, although largely observational, suggests that exposure to certain HMOs—particularly fucosylated and sialylated structures such as 2'-fucosyllactose (2'-FL), 3'-sialyllactose (3'-SL), and 6'-sialyllactose (6'-SL)—may be associated with improved neurodevelopmental outcomes. Infants exposed to higher levels of these HMOs during early life have been reported to show better cognitive performance, language development, and behavioral regulation. Early-life exposure appears especially important, as this period coincides with rapid brain growth and neural network formation. Several biological mechanisms may explain these associations. HMOs influence the gut–brain axis by promoting beneficial microbiota, particularly *Bifidobacterium*, which produce metabolites that can affect neural signaling and brain development. Additionally, sialylated HMOs provide sialic acid, a key component required for the synthesis of gangliosides and myelin that support neuronal connectivity and signal transmission. HMOs may also contribute to immune regulation and anti-inflammatory processes, helping to protect the developing brain from inflammatory stress. Despite promising findings, causal evidence remains limited. Most studies are observational and vary in design, HMO measurement methods, and participant characteristics. Important confounding factors, including maternal secretor status, breastfeeding duration, maternal nutrition, and socioeconomic influences, may affect observed associations. Furthermore, randomized controlled trials investigating direct neurodevelopmental effects of specific HMOs are still scarce. Future research should prioritize standardized HMO quantification, larger longitudinal cohorts, integration of

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neuroimaging techniques, and well-designed interventional trials to better clarify the role of HMOs in early brain development and long-term cognitive outcomes.

Keywords

Human Milk Oligosaccharides (HMOs), Infant Neurodevelopment, Cognitive Function, Gut–brain Axis, Fucosylated HMOs, Sialylated HMOs, Language Development, Myelination

1. Introduction

Infancy and early childhood represent periods of rapid brain growth and development. Structural processes such as myelination, synaptogenesis, synaptic pruning, and neural connectivity establish foundational circuits for cognition, language, motor skills, and socio-emotional behavior. Any nutritional, microbial, immunologic, or environmental insults during this period can have lasting effects [1].

Human milk is not merely a source of calories and basic nutrients, but contains multiple bioactive components (e.g. immunoglobulins, growth factors, microbiota, human milk oligosaccharides) that influence infant development. Among

these, HMOs are a group of structurally diverse, non-digestible oligosaccharides, which represent the third-largest solid component in human milk after lactose and lipids [2].

Although HMOs were first studied mainly for their roles in pathogen blocking, prebiotic activity, and immune modulation, recent research has begun to examine associations between HMO exposure and neurodevelopmental outcomes in infants, as well as mechanistic evidence from animal studies. This review aims to summarize the literature on HMOs and infant neurodevelopment, discuss mechanisms, identify gaps, and suggest future directions.

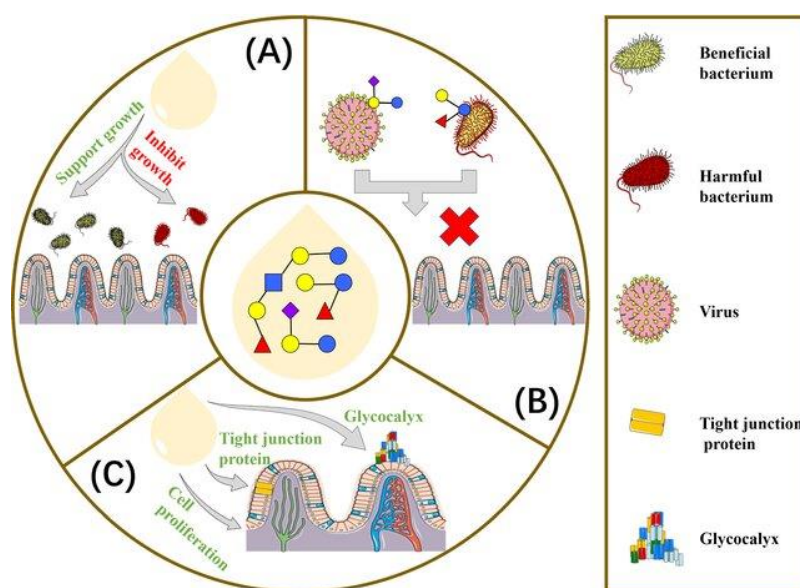


Figure 1. Schematic summary of main effects of HMOs [28].

2. Review Methodology

This manuscript is a narrative review aimed at synthesizing current evidence on the relationship between human milk oligosaccharides (HMOs) and infant neurodevelopment. A structured literature search was conducted using PubMed, Scopus, and Web of Science databases covering publications from Jan-

uary 2000 to March 2025. Search terms included combinations of “human milk oligosaccharides,” “HMO,” “2'-fucosyl-lactose,” “sialyllactose,” “infant neurodevelopment,” “cognition,” “language development,” “myelination,” and “gut–brain axis.”

Studies were prioritized if they: (1) reported quantified HMO concentrations in human milk, (2) assessed neurodevelopmental outcomes using validated tools (e.g., Bayley Scales, ASQ, neuroimaging biomarkers), or (3) provided mechanistic

insights through experimental or preclinical models. Both observational human cohort studies and relevant animal investigations were included to provide biological plausibility. Emphasis was placed on studies evaluating early-life exposure windows and specific HMO structures (e.g., fucosylated and sialylated species) [3-5].

As a narrative review, formal systematic review procedures (e.g., PRISMA screening flow) were not applied; however, efforts were made to ensure balanced representation of available evidence and to highlight areas of consistency, heterogeneity, and research gap.

3. Human Studies: Structured Evidence on HMOs and Neurodevelopment

3.1. Evidence by Cognitive Domains

3.1.1. Cognitive Development

Several observational cohort studies have reported associations between early-life exposure to specific HMOs and cognitive performance in infancy and toddlerhood. Higher concentrations of fucosylated HMOs—particularly 2'-fucosyllactose (2'-FL)—measured at approximately one month postpartum have been associated with higher composite cognitive scores at 18–24 months of age. These findings are most consistently reported in full-term breastfed cohorts, although effect sizes vary across studies. Importantly, the majority of available evidence remains observational, limiting causal inference [6].

3.1.2. Language Development

Language outcomes appear particularly sensitive to early HMO exposure. Both fucosylated and sialylated HMOs, including 2'-FL and 6'-sialyllactose (6'-SL), have been linked to higher receptive and expressive language scores during toddlerhood. Some studies suggest that early exposure (e.g., at 1 month) demonstrates stronger associations than later exposure (e.g., at 6 months), supporting the hypothesis of critical developmental windows [7].

3.1.3. Motor and Socio-emotional Development

Associations between HMOs and motor development are reported less consistently but have been observed in several cohorts. Socio-emotional outcomes have shown associations particularly with sialylated HMOs such as 6'-SL. In some neuroimaging studies, structural brain markers (e.g., myelin water fraction) partially mediated associations between HMO exposure and social or language performance, suggesting potential biological pathways linking milk composition to functional outcomes.

3.2. Evidence by Specific HMO Structures

3.2.1. Fucosylated HMOs (e.g., 2'-FL, 3'-FL)

Fucosylated HMOs are among the most extensively studied in human cohorts. 2'-FL, in particular, has been repeatedly associated with higher cognitive and language scores in infancy. Maternal secretor status, which strongly influences 2'-FL concentration, appears to modify exposure levels, although its moderating role on developmental outcomes remains inconsistent across studies. Overall, fucosylated HMOs demonstrate the most consistent observational associations with cognitive domains [8, 9].

3.2.2. Sialylated HMOs (e.g., 3'-SL, 6'-SL)

Sialylated HMOs have been associated with both functional and structural markers of neurodevelopment. 6'-SL has been linked to myelination measures in neuroimaging studies and to socio-emotional and language outcomes in observational cohorts. Given that sialylated HMOs provide sialic acid—a key component of neuronal membranes and gangliosides—their associations with structural brain development are biologically plausible.

3.3. Evidence by Mechanistic Categories

3.3.1. Gut–brain Axis Mediation

HMOs function as prebiotics that selectively promote beneficial bacteria such as *Bifidobacterium* species. Fermentation of HMOs produces short-chain fatty acids (SCFAs) and other metabolites that may influence systemic inflammation, blood–brain barrier integrity, and microglial maturation. Although human evidence directly linking microbiome shifts to neurodevelopmental outcomes remains limited, preclinical studies support this pathway as biologically plausible [14, 15].

3.3.2. Nutrient Provision and Myelination (Mechanistic Link Between Sialylated HMOs and Myelination)

Sialylated HMOs, such as 3'-sialyllactose (3'-SL) and 6'-sialyllactose (6'-SL), may influence early brain development through their contribution of sialic acid, a critical component of gangliosides and glycoproteins in neuronal membranes. Sialic acids are highly concentrated in the developing brain and play essential roles in neurite outgrowth, synaptogenesis, cell–cell recognition, and signal transmission. Importantly, sialic acid is a structural constituent of myelin-associated glycoproteins and gangliosides that are required for oligodendrocyte maturation and axonal insulation.

During infancy—a period characterized by rapid myelination—adequate availability of sialic acid may support efficient myelin membrane synthesis and stabilization. Experimental models suggest that dietary sialic acid supplementation

enhances brain ganglioside content and may improve learning-related outcomes. Observational human studies linking higher concentrations of 6'-SL to increased myelin water fraction provide indirect structural support for this pathway. Although direct causal confirmation in human infants remains limited, the biological plausibility of sialylated HMOs contributing to myelin formation represents a compelling mechanistic hypothesis that warrants further investigation through neuroimaging-integrated clinical studies [16, 17].

3.3.3. Immune Modulation and Anti-inflammatory Effects

HMOs modulate immune signaling and enhance gut barrier integrity, potentially reducing systemic inflammatory exposure during critical periods of brain development. Because chronic inflammation is known to interfere with neuronal maturation and connectivity, this pathway may indirectly support neurodevelopmental outcomes.

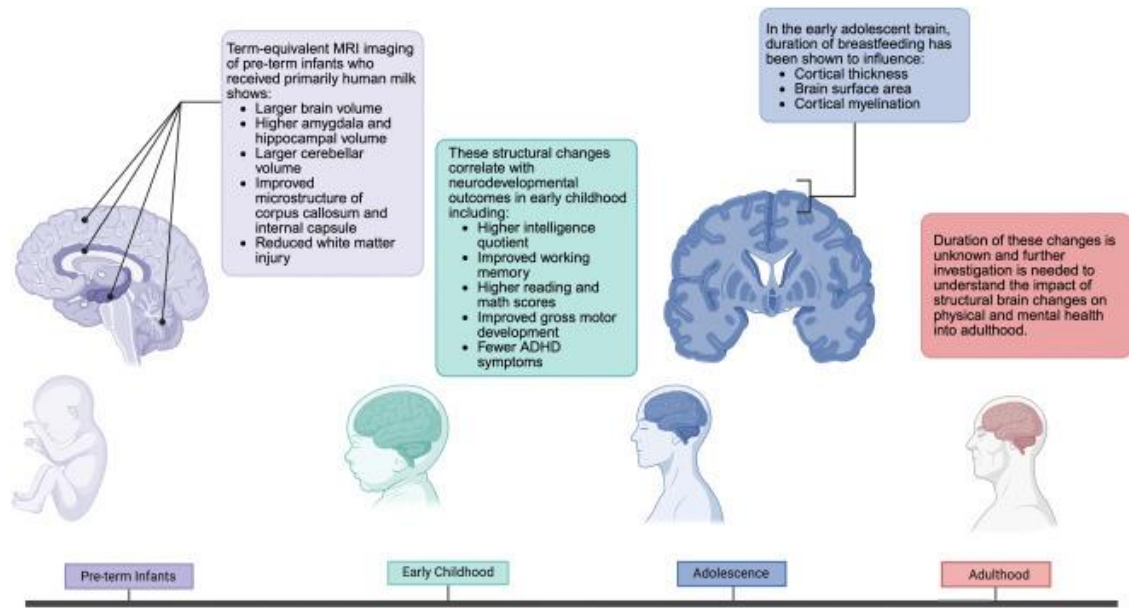


Figure 2. Impact of human milk exposure on brain structure and neurodevelopmental outcomes across the lifespan. Figure created in BioRender [10].

Table 1. Major Human Studies Examining Human Milk Oligosaccharides (HMOs) and Infant Neurodevelopment [23, 24].

Study (Year)	Cohort Size	Infant Population	HMOs Measured	Age at Outcome Assessment	Neurodevelopmental Domain	Key Findings
Berger et al. (2023)	35–659 (across cohorts)	Full-term infants	2'-FL, 3-FL, 3'-SL, 6'-SL	18–24 months	Cognitive, Language, Motor	Early exposure to specific fucosylated and sialylated HMOs associated with higher developmental scores
Neuroimaging Cohort Study	~100	Healthy term infants	6'-SL, fucosylated HMOs	6–24 months	Myelination, Language, Socio-emotional	6'-SL associated with increased myelin water fraction; structural markers correlated with functional outcomes
Longitudinal HMO Cohort	~200	Breastfed term infants	2'-FL, total fucosylated HMOs	24 months	Cognitive	Higher 2'-FL at 1 month associated with improved cognitive composite scores
Multi-HMO Analysis Study	~150	Term infants	Broad HMO profile (LC–MS)	12–24 months	Language, Motor	Associations varied by HMO structure; strongest effects seen with

Study (Year)	Cohort Size	Infant Population	HMOs Measured	Age at Outcome Assessment	Neurodevelopmental Domain	Key Findings
Secretor Status Study	~100	Term infants (secretor vs non-secretor mothers)	2'-FL, related fucosylated HMOs	18–24 months	Cognitive, Language	fucosylated species Secretor-derived milk associated with differential developmental trajectories; findings heterogeneous

4. There Is Growing Evidence That HMOs Affect Infant Neurodevelopment

4.1. Strengths of the Evidence [11]

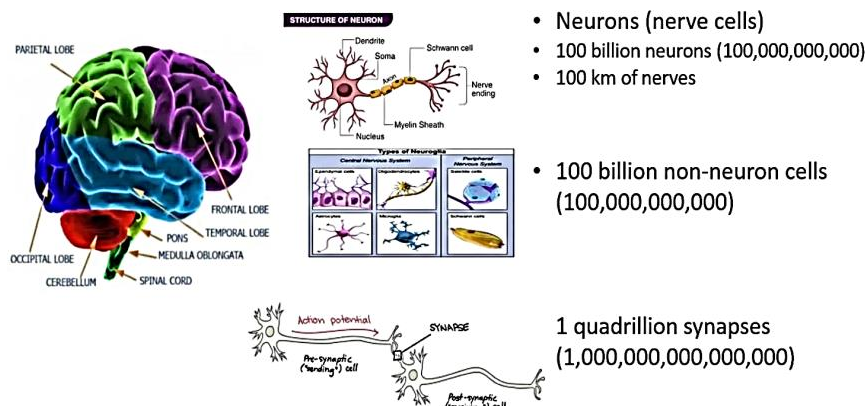


Figure 3. Human Milk Oligosaccharides (HMOs) and Brain Development [12].

Multiple observational human studies converge in showing positive associations between HMOs (especially fucosylated and sialylated types) and neurodevelopment outcomes across cognitive, language, motor, and social-emotional domains.

Animal and mechanistic studies bolster plausibility by showing effects on brain structure (e.g. LTP, memory tasks, myelination) and demonstrating potential biological pathways.

Some human studies include neuroimaging (e.g. myelin water fraction) to provide structural correlates [22, 25].

4.2. Limitations and Gaps in HMO Related Studies [13, 26]

Despite growing interest in the relationship between human milk oligosaccharides (HMOs) and infant neurodevelopment, several important limitations constrain interpretation of the current evidence.

First, the predominance of observational study designs limits its causal inference. Although multiple cohorts report associations between specific HMOs and neurodevelopmental outcomes, residual confounding cannot be excluded. Breastfeeding exclusivity, maternal education, socioeconomic status, home stimulation, maternal diet, and infection history may in-

dependently influence both milk composition and developmental trajectories.

Second, maternal genetic variation—particularly secretor status (FUT2 gene expression)—substantially influences the concentration of fucosylated HMOs such as 2'-fucosyllactose. While some studies adjust for secretor status, its potential role as an effect modifier remains inconsistently evaluated. Failure to account for genetic determinants of milk composition may introduce heterogeneity across findings [27].

Third, methodological variability in HMO quantification presents a major challenge. Differences in analytical platforms (e.g., HPLC, LC–MS/MS, mass spectrometry profiling), timing of milk sampling (colostrum vs. mature milk; 1 month vs. 6 months), and number of HMOs measured limit cross-study comparability. Standardization of laboratory methods and reporting practices is needed to strengthen reproducibility.

Fourth, neurodevelopmental assessment tools differ substantially across studies. Investigators have used various psychometric instruments (e.g., Bayley Scales of Infant Development, Ages and Stages Questionnaire, parent-reported measures) at different ages, contributing to outcome heterogeneity. Moreover, relatively few studies integrate objective neuroimaging biomarkers, such as myelin water fraction or

diffusion tensor imaging, which could provide structural correlates of functional findings [28].

Fifth, sample sizes are often modest, and most available data derive from full-term infants in high-income settings. Preterm infants, who may be particularly vulnerable to altered neurodevelopmental trajectories, remain underrepresented. Additionally, limited representation of low- and middle-income populations restricts generalizability.

Finally, there is a paucity of randomized controlled trials specifically designed to manipulate HMO exposure and evaluate long-term neurodevelopmental endpoints. Without controlled interventional data, translation into clinical or nutritional recommendations must remain cautious.

Addressing these limitations through standardized assays, harmonized developmental outcome measures, adequately powered multicenter cohorts, inclusion of diverse populations, and rigorously designed interventional trials will be essential to clarify the true magnitude and clinical relevance of HMO-related neurodevelopmental effects.

4.3. Implications [18, 19]

- 1) Potential for using HMOs (or HMO-enriched formulas/milk - based supplements) as nutritional interventions to support neurodevelopment, especially in settings where breastfeeding is suboptimal.
- 2) Timing matters: early exposure (first month) seems particularly important. Interventions may need to begin very early to maximize benefit [20].
- 3) Specific HMOs may differ in effect; not all are equal. Fucosylated and sialylated HMOs are among most promising [21].

5. Conclusion

Current evidence suggests that human milk oligosaccharides (HMOs) may play a role in infant neurodevelopment. Observational studies in full-term infants have reported associations between early exposure to specific fucosylated and sialylated HMOs—such as 2'-FL, 3'-FL, 3'-SL, and 6'-SL—and improved cognitive, language, motor, and socio-emotional outcomes. Preclinical findings provide biological plausibility through mechanisms involving the gut-brain axis, sialic acid provision, inflammation regulation, and support of myelination.

However, most human data remain observational, limiting causal conclusions. Well-designed clinical trials, standardized HMO measurement, and inclusion of diverse infant populations are needed to clarify the clinical relevance of HMOs in supporting early brain development.

Author Contributions

Gazi Imranul Haque: Conceptualization, Methodology,

Resources, Investigation, Supervision, Writing – original draft, Writing – review & editing

Rezanur Rahman: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing

Urmi Roy: Data curation, Investigation, Resources, Visualization, Writing – original draft, Writing – review & editing

Sharmin Sultana: Methodology, Investigation, Validation, Resources, Writing – original draft, Writing – review & editing

Abu Sayed: Data curation, Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing

Shamiha Seraj: Investigation, Methodology, Validation, Resources, Writing – original draft, Writing – review & editing

Shakibur Rahman: Supervision, Project administration, Validation, Writing – review & editing

Conflicts of Interest

Authors declared no conflicts of interest.

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