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Gut Microbial Imbalance and Neurodevelopmental Disorders: Exploring the Gut's Role in Brain Health

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Abstract

The gut microbiota plays a crucial role in brain development and function, influencing various neurodevelopmental disorders (NDDs) such as autism spectrum disorder (ASD), attention-deficit/hyperactivity disorder (ADHD), and intellectual disabilities (ID). Dysbiosis, or an imbalance in the gut microbiota, has been linked to altered neuroinflammation, impaired blood-brain barrier (BBB) integrity, and changes in neurotransmitter production, all of which contribute to NDD pathophysiology. Research has highlighted microbial signatures and metabolites, such as short-chain fatty acids (SCFAs), as potential biomarkers for NDDs, making gut microbiota an exciting area for diagnostic and therapeutic strategies. Early-life factors, including maternal health, delivery mode, diet, and antibiotic use, can significantly influence gut microbiota composition, thus affecting neurodevelopmental outcomes in offspring. Despite these promising findings, several challenges remain in translating gut microbiota research into clinical practice. Variability in individual microbiota profiles and a lack of standardized analysis methods complicate the identification of universal biomarkers for NDDs. Furthermore, while microbiota-targeted therapies like probiotics and dietary interventions have shown promise in preclinical and early clinical studies, a deeper understanding of the mechanisms driving the gut-brain connection is needed. As advancements in microbiome profiling, metabolomics, and non-invasive diagnostic techniques continue, there is potential for more personalized, effective interventions that can monitor, predict, and treat NDDs, improving patient outcomes and transforming clinical approaches to neurodevelopmental care.

Keywords

Gut microbiota, Neurodevelopmental disorders, Dysbiosis, Autism spectrum disorder, Attention-deficit/hyperactivity disorder, Short-chain fatty acids, Probiotics

Introduction

NDDs are a group of conditions characterized by impairments in the development of the central nervous system (CNS), which typically emerge during early childhood and have long-lasting effects on cognitive, emotional, social, and motor functioning [1]. Common examples include ASD, ADHD, ID, specific learning disorders, and communication disorders (Table 1) [1]. These conditions often have overlapping symptoms and may co-occur, posing challenges for diagnosis and treatment. The term "neurodevelopmental" underscores that these disorders stem from atypical brain development during critical periods of growth, influenced by both genetic and environmental factors [2].

Statistical data indicates the global prevalence of NDDs varies significantly across populations and diagnostic criteria. For instance, ASD affects approxi-

Table 1: Common NDDs, their characteristics and symptoms.

NDD	Key characteristics	Common symptoms
ASD	A spectrum of disorders affecting social communication, behavior, and sensory processing	Social difficulties, repetitive behaviors, and communication challenges
ADHD	NDDs characterized by persistent inattention, hyperactivity, and impulsivity	Inattention, hyperactivity, impulsiveness, and poor impulse control
ID	Cognitive impairment, affecting learning, problem-solving, and intellectual functioning	Below-average IQ, difficulties with academic and adaptive skills
Schizophrenia	A chronic mental health condition that impacts thinking, emotional regulation, and behavior	Hallucinations, delusions, disorganized thinking, and cognitive deficits
Developmental coordination disorder	Impairment in motor coordination that affects daily activities and academic performance	Poor motor skills, difficulty with tasks requiring fine or gross motor control
Tic disorders (including Tourette syndrome)	Characterized by involuntary movements and vocalizations (tics)	Motor tics, vocal tics, and repetitive behaviors
Cerebral palsy (CP)	A group of disorders affecting movement, muscle tone, and motor skills, caused by brain damage	Muscle weakness, spasticity, coordination problems, and difficulty with posture

mately 1 in 100 children worldwide, while ADHD is estimated to have a prevalence of 5 to 7% in children and adolescents [3]. IDs impact about 1% of the population, with many cases linked to genetic conditions like down syndrome or Fragile X syndrome [3]. Advances in diagnostic techniques, such as neuroimaging and genetic testing, have contributed to better understanding and detection of these disorders. However, disparities in access to diagnostic tools and healthcare services result in underdiagnosis, especially in low- and middle-income countries, exacerbating health inequalities [4].

From a scientific perspective, NDDs arise due to a complex interplay between genetic, environmental, and epigenetic factors [1]. Genetic contributions are well-documented, with studies highlighting the involvement of hundreds of genes associated with brain development and neural connectivity. For example, mutations in genes like CHD8 and SCN2A have been linked to ASD, while variations in the dopamine transporter gene are associated with ADHD [5]. Environmental factors such as prenatal exposure to toxins, infections, or nutritional deficiencies can exacerbate genetic susceptibilities, disrupting critical periods of neurodevelopment [6]. Advances in neuroimaging reveal that structural and functional abnormalities in brain regions, such as the prefrontal cortex, amygdala, and cerebellum, often underlie the symptoms of NDDs [1].

The rising prevalence of NDDs and their impact on individuals, families, and society underscore the importance of ongoing research and public health initiatives. Early detection methods, like genetic testing and behavioral assessments, combined with therapeutic approaches, including behavioral interventions, pharmacological treatments, and educational support, are pivotal in addressing the needs of those affected [7]. Furthermore, increasing awareness and reducing stigma surrounding these disorders remain essential to fostering inclusivity and improving long-term outcomes for individuals with neurodevelopmental challenges [8].

Role of Gut Microbiota in NDDs

The gut microbiota, a diverse community of microorganisms residing in the gastrointestinal tract, has emerged as a key player in influencing brain function and behavior (Figure 1) [9].

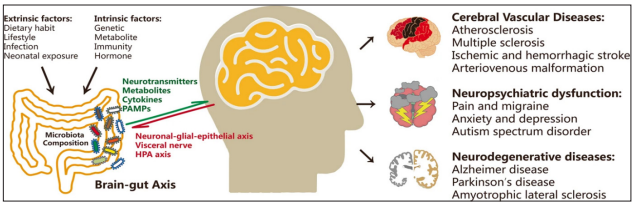


Figure 1: Influence of gut microbiota on brain development [9].

This gut-brain axis, a bidirectional communication system between the CNS and the gut, involves neural, hormonal, immune, and metabolic pathways [9]. Increasing evidence suggests that disruptions in gut microbiota composition, termed dysbiosis, may contribute to the development and progression of NDDs such as ASD, ADHD, and ID (Table 2) [9]. These findings highlight the gut as a potential therapeutic target for mitigating symptoms and improving outcomes in individuals with NDDs.

One prominent area of research focuses on ASD, where altered gut microbiota profiles have been frequently reported. Studies have shown that children with ASD exhibit reduced diversity of gut bacteria, an overrepresentation of certain pathogenic species (e.g., *Clostridium* and *Desulfovibrio*), and lower levels of beneficial bacteria like *Bifidobacterium* and *Lactobacillus*. Dysbiosis in ASD is thought to affect brain function through various mechanisms, including the production of neuroactive metabolites such as SCFAs. For instance, SCFAs like butyrate play a role in maintaining the integrity of the BBB and regulating neuroinflammation, while their imbalance may contribute to the atypical neural development observed in ASD [10, 11].

The gut microbiota also influences neurodevelopment through its impact on the immune system. Dysbiosis can lead to a heightened inflammatory response, marked by increased levels of pro-inflammatory cytokines. Inflammation has been linked to altered synaptic pruning and impaired neural connectivity, which are critical processes during brain development [12]. For example, in ADHD, systemic inflammation driven by gut microbiota imbalances may affect dopamine signaling pathways, which are integral to attention and impulse control. Similarly, maternal gut microbiota during pregnancy plays a vital role in shaping the offspring's immune system

Table 2: Relationship between various NDDs and gut microbiota, including potential microbial imbalances, key findings, and implications [9].

NDD	Gut microbiota connection	Gut microbiota changes	Key findings	Implications
ASD	Altered gut microbiota composition, such as reduced *Bifidobacterium* and higher *Clostridium* levels, linked to gastrointestinal symptoms and neuroinflammation.	Reduced diversity of gut microbiota, altered levels of Bacteroides, *Clostridium*, and *Bifidobacterium*.	Children with ASD show higher levels of *C. bolteae* and decreased *Bifidobacterium* abundance.	Microbial dysbiosis may contribute to ASD-related gastrointestinal symptoms and neuroinflammation.
ADHD	Gut microbiota imbalances (e.g., increased Firmicutes and Bacteroides) may influence brain function and behavior.	Reduced microbial diversity, higher levels of Firmicutes and Bacteroides.	Studies suggest a higher prevalence of gut inflammation and dysbiosis in ADHD children.	Gut health interventions like probiotics may help manage ADHD symptoms by restoring microbial balance.
ID	Reduced *Lactobacillus* and *Bifidobacterium* abundance, leading to gastrointestinal disturbances, which may exacerbate cognitive symptoms.	Imbalanced gut microbiota with reduced *Lactobacillus* and *Bifidobacterium* levels.	Research shows that children with ID often have gastrointestinal issues linked to microbial imbalances.	Restoring gut microbiota might improve gastrointestinal symptoms and cognitive function.
Schizophrenia	Dysbiosis with an overrepresentation of Firmicutes and Proteobacteria may contribute to neuroinflammation and cognitive dysfunction.	Increased levels of Firmicutes, Proteobacteria, and decreased *Bifidobacterium*.	Dysbiosis in schizophrenia may lead to neuroinflammation and altered brain function.	Gut-targeted therapies may reduce inflammation and improve cognitive outcomes.
Developmental coordination disorder	Gut microbiota imbalances may correlate with motor coordination difficulties and neurodevelopmental delays.	Altered gut microbiota with shifts in Firmicutes and Bacteroides.	DCD children have shown altered gut microbiomes, which may correlate with motor coordination impairments.	Modulating gut microbiota could potentially improve coordination and related developmental delays.
Tic disorders (including tourette syndrome)	Increased Streptococcus levels and other microbial changes are associated with tics and neuroinflammation.	Higher levels of Streptococcus and reduced microbial diversity.	Studies show a possible connection between gut inflammation and the severity of tics.	Gut microbiota modulation might offer a complementary approach to managing tics.
CP	Altered gut microbiota, with reduced *Bifidobacterium* and *Lactobacillus*, linked to gastrointestinal issues commonly seen in CP.	Altered gut microbiota with lower *Bifidobacterium* and *Lactobacillus*.	Children with CP often present with gut issues and reduced microbial diversity, affecting overall health.	Modifying gut flora may improve health outcomes and reduce associated gastrointestinal problems.

and neurodevelopment. Disruptions during this critical period, such as maternal infections or an imbalanced microbiome, can increase the risk of NDDs in the child [13].

Another important factor is the gut's production of neurotransmitters and neuromodulators. Certain gut bacteria synthesize compounds like serotonin, gamma-aminobutyric acid, and dopamine, which directly influence brain function. Alterations in these microbiota-derived neurochemicals may contribute to the behavioral and emotional dysregulation seen in NDDs. For instance, reduced levels of serotonin-a neurotransmitter linked to mood, anxiety, and social behavior-have been associated with gut dysbiosis in ASD. Furthermore, metabolites from pathogenic bacteria can have neurotoxic effects, disrupting neuronal activity and exacerbating NDD symptoms [14, 15].

Targeting gut microbiota is a growing area of therapeutic interest for NDDs. Interventions such as probiotics, prebiotics, dietary modifications, and fecal microbiota transplantation (FMT) have shown promise in modulating gut microbiota composition and improving behavioral outcomes [16]. Preliminary studies in children with ASD have reported improvements in social interaction and communication following probiotic supplementation or FMT. While these findings are encouraging, further research is needed to elucidate the complex interplay between the gut microbiota and neurodevelopment [17]. Future studies should also explore personalized approaches, considering the unique microbiome profiles of individuals with NDDs, to optimize treatment strategies and maximize therapeutic benefits [18].

Factors Influencing Gut Microbiota and Their Impact on NDDs

The gut microbiota, a dynamic microbial community in the gastrointestinal tract, plays a critical role in shaping brain development and is influenced by a variety of factors. Key determinants include maternal health, mode of delivery, early-life diet, antibiotic use, environmental exposures, and stress, all of which can disrupt gut microbial composition and contribute to NDDs [19, 20]. Understanding these factors provides insight into potential therapeutic strategies targeting the gut-brain axis to mitigate NDD symptoms and improve neurodevelopmental outcomes.

Maternal health and prenatal factors

The composition of gut microbiota is significantly influenced by maternal health and prenatal conditions, which can have long-lasting impacts on neurodevelopmental outcomes in offspring. Factors such as maternal diet, stress, infections, and antibiotic use during pregnancy shape the gut microbiota of the developing fetus [21]. For instance, maternal immune activation (MIA) triggered by infections can disrupt the maternal microbiome and increase inflammatory cytokines,

which cross the placenta and affect fetal brain development. A study on MIA in animal models found that altered maternal gut microbiota during pregnancy contributed to ASD-like behaviors in offspring. Restoring the maternal microbiota using specific probiotics, such as *Lactobacillus* or *Bacteroides fragilis*, reduced these adverse outcomes, emphasizing the critical role of maternal microbiota in neurodevelopment [22, 23].

Mode of delivery

The mode of birth-vaginal delivery or cesarean section plays a crucial role in establishing the initial gut microbiota of the newborn. Infants born through vaginal delivery are colonized by beneficial bacteria from the maternal vaginal and intestinal microbiota, such as *Lactobacillus* and *Bifidobacterium*. In contrast, cesarean-delivered infants are exposed to skin-associated bacteria like *Staphylococcus* species, resulting in delayed microbial diversity [24, 25]. This altered microbial colonization has been linked to a higher risk of developing NDDs such as ADHD and ASD. A study found that cesarean-born mice exhibited behavioral deficits linked to reduced gut microbial diversity and impaired brain development. Supplementation with probiotics restored normal behaviors, demonstrating the importance of early microbial exposure [26].

Dietary influences in early life

The infant's diet, particularly breastfeeding versus formula feeding, profoundly affects gut microbiota composition. Breast milk contains oligosaccharides that promote the growth of beneficial bacteria like *Bifidobacterium*, which play a critical role in immune development and neuroprotection. Formula-fed infants often display lower microbial diversity and higher colonization by potentially pathogenic bacteria [27, 28]. For example, reduced levels of *Bifidobacterium* have been observed in children with ASD, alongside increased gut inflammation [29]. A study highlighted that breastfeeding was associated with better cognitive and behavioral outcomes due to the beneficial effects of gut microbiota on brain development. Dietary interventions, such as enriching formulas with prebiotics or probiotics, have shown promise in mimicking the neurodevelopmental benefits of breastfeeding [30].

Antibiotic use

Antibiotics, especially when used during early childhood, can disrupt gut microbiota by killing both pathogenic and beneficial bacteria. This dysbiosis during critical windows of brain development has been associated with an increased risk of NDDs [31]. For instance, a study in mice demonstrated that neonatal antibiotic exposure led to long-term alterations in gut microbiota and anxiety-like behaviors [32]. Similarly, in humans, frequent antibiotic use in the first two years of life has been linked to an increased prevalence of ADHD and ASD. The overgrowth of antibiotic-resistant bacteria and a reduction in SCFA-producing microbes are thought to impair brain development by increasing systemic inflammation and reducing neuroprotective signals [33].

Environmental exposures

Environmental factors, such as exposure to pollutants, heavy metals, and pesticides, can influence gut microbiota and contribute to the pathogenesis of NDDs. For example, glyphosate, a widely used pesticide, has been shown to disrupt gut microbial composition by targeting beneficial bacteria [34]. A study reported that glyphosate exposure in animal models led to gut dysbiosis and ASD-like behaviors [35]. Similarly, heavy metals like lead and mercury, which are known neurotoxins, alter the gut microbiome and increase gut permeability. This "leaky gut" state allows microbial metabolites and toxins to enter the bloodstream, potentially compromising the BBB and triggering neuroinflammation [36].

Stress and psychosocial factors

Stress, both in early life and during critical developmental periods, significantly alters gut microbiota composition. For example, maternal stress during pregnancy has been linked to increased levels of stress hormones like cortisol, which influence the maternal and fetal microbiomes. Postnatally, adverse childhood experiences, such as abuse or neglect, have been associated with gut dysbiosis and an increased risk of NDDs like ADHD [37, 38]. Animal studies have shown that early-life stress alters gut microbiota, leading to long-term changes in brain function and behavior. For instance, germ-free mice subjected to stress exhibited anxiety-like behaviors and reduced hippocampal plasticity, which were normalized after FMT from non-stressed mice [39, 40].

Genetic and epigenetic interactions

Genetic predispositions also shape the gut microbiota and influence its impact on neurodevelopment. Certain genetic mutations linked to NDDs, such as those in the SHANK3 gene associated with ASD, have been shown to alter gut microbial composition [17]. Conversely, gut microbiota can influence gene expression in the brain through epigenetic mechanisms, such as DNA methylation and histone modification. For example, SCFAs produced by gut bacteria can regulate the expression of genes involved in synaptic plasticity and neuroinflammation. This bidirectional interaction underscores the complexity of the relationship between genetics, gut microbiota, and NDDs [41].

Probiotics and dietary interventions

Given the influence of gut microbiota on NDDs, probiotics and dietary interventions have emerged as promising therapeutic strategies. Probiotics like *Lactobacillus* and *Bifidobacterium* have been shown to improve behavioral outcomes in animal models of ASD and ADHD by restoring gut microbiota balance and reducing inflammation. Similarly, prebiotic-rich diets, which promote the growth of beneficial gut bacteria, have been associated with improved cognitive function and social behavior [10, 42]. For example, a clinical trial found that probiotic supplementation in children with ASD improved gut health and reduced irritability and anxiety. These findings highlight the potential of gut-targeted therapies to mitigate the symptoms of NDDs and improve quality of life [43].

Implications of Gut Microbiota to Monitor NDDs

The gut microbiota plays a critical role in neurodevel-

opment and offers promising opportunities for monitoring NDDs. Alterations in gut microbial composition, metabolites, and immune markers have been linked to NDD pathophysiology, making them valuable indicators for early detection, tracking disease severity, and evaluating treatment efficacy. Leveraging gut microbiota as a diagnostic and prognostic tool could revolutionize personalized care and preventive strategies for individuals at risk of NDDs [44].

Gut microbiota as a diagnostic biomarker

The gut microbiota offers a promising avenue for identifying biomarkers to monitor NDDs such as ASD and ADHD. Studies have demonstrated distinct microbial profiles in individuals with NDDs compared to neurotypical individuals, with changes in diversity and the relative abundance of specific bacterial species like *Bacteroides*, *Clostridium*, and *Lactobacillus*. For instance, reduced levels of *Bifidobacterium* and elevated levels of *Clostridium bolteae* have been consistently observed in children with ASD. Monitoring these microbial signatures could serve as a non-invasive, cost-effective tool for early detection and tracking the progression of NDDs, offering a valuable complement to behavioral and clinical assessments [45, 46].

Monitoring disease severity and treatment response

Changes in gut microbiota composition could also be used to monitor the severity of symptoms and the efficacy of treatments in individuals with NDDs. For example, interventions such as probiotics, prebiotics, dietary modifications, and FMT aim to restore microbial balance and have shown promise in improving behavioral and cognitive outcomes. Tracking microbiota changes before, during, and after treatment could provide insights into therapeutic efficacy. In a clinical trial involving children with ASD, improvements in social and communication skills after FMT were associated with increased microbial diversity and a reduction in pathogenic bacteria. This demonstrates the potential of gut microbiota analysis as a dynamic marker for assessing treatment impact [47].

Real-time monitoring via microbiota-associated metabolites

Microbial metabolites, such as SCFAs, neurotransmitters, and toxins, are critical indicators of gut-brain interactions and can serve as biochemical markers for NDDs. SCFAs like butyrate and propionate are known to influence neuroinflammation, synaptic plasticity, and the BBB, and their altered levels have been linked to ASD and ADHD. Monitoring the concentrations of these metabolites in stool or blood samples could provide a real-time picture of gut microbiota functionality and its impact on brain health. Additionally, advancements in metabolomics and high-throughput sequencing could enable the detection of these metabolites with high precision, facilitating early interventions and personalized treatment approaches [48, 49].

Potential for predictive and preventive strategies

The ability to monitor gut microbiota over time opens the door to predictive and preventive strategies for NDDs. For example, tracking gut microbiota during critical developmental windows, such as infancy and early childhood, could help identify individuals at higher risk of NDDs based on early microbial imbalances. Preventive measures, such as targeted dietary interventions or probiotic supplementation, could then be implemented to reduce the likelihood of developing NDD-related symptoms. Furthermore, longitudinal monitoring of gut microbiota in high-risk populations-such as children with a family history of ASD could allow clinicians to anticipate and mitigate the onset of neurodevelopmental deficits, paving the way for proactive care strategies [50, 51].

Immune monitoring in NDDs

The relationship between the gut microbiota and the immune system is critical in understanding and monitoring NDDs. Dysbiosis in the gut can trigger chronic low-grade inflammation by increasing pro-inflammatory cytokines, such as IL-6 and TNF-α, which have been implicated in conditions like ASD and ADHD [52]. By monitoring changes in immune markers influenced by gut microbiota, healthcare professionals could identify early signs of inflammation-associated neurodevelopmental impairments. For example, elevated levels of lipopolysaccharides, a byproduct of certain gut bacteria, are linked to increased gut permeability and neuroinflammation in ASD patients. These markers could serve as early red flags for NDDs, and guide tailored anti-inflammatory or gut-targeted treatments [53].

Microbial profiling for personalized interventions

Advances in microbial sequencing technologies, such as 16S rRNA sequencing and metagenomic analysis, have enabled comprehensive profiling of gut microbiota. These tools can be used to monitor individual microbial compositions and personalize interventions for children with NDDs [54]. For instance, children with a predominance of pro-inflammatory bacteria like *Clostridium* or reduced beneficial species like *Bifidobacterium* may benefit from targeted probiotic or dietary therapies [55]. A study showed that children with ASD who received personalized microbiota-based therapies demonstrated improvements in gastrointestinal symptoms and social behaviors. By regularly monitoring microbial profiles, clinicians can fine-tune interventions to maximize benefits, making gut microbiota a cornerstone of precision medicine in NDD care [56].

Longitudinal studies to track neurodevelopmental trajectories

Longitudinal studies involving gut microbiota monitoring can shed light on the dynamic interplay between the microbiome and neurodevelopmental trajectories. Regular sampling of gut microbiota from infancy to adolescence in individuals with NDDs could help track the evolution of microbial communities alongside neurodevelopmental progress [57]. For instance, a study found that early-life disruptions in gut microbiota due to antibiotics led to long-term changes in microbial composition and increased susceptibility to ASD-like behaviors. Such studies highlight the potential for using gut microbiota as a continuous marker to predict and adapt treatment strategies based on developmental stages, offering a holistic approach to managing NDDs over time [58].

Ethical and practical considerations

Despite the promising implications of gut microbiota monitoring for NDDs, several ethical and practical considerations must be addressed. Regular stool or blood sampling for microbiota analysis could pose logistical challenges and discomfort for young children, especially those with sensory sensitivities often seen in ASD [59]. Additionally, the interpretation of microbiota data is complex, as individual variability and environmental factors like diet and medication can influence results. Ethical considerations also arise regarding data privacy and the potential stigmatization of children based on microbiota profiles. Addressing these challenges through standardized protocols, non-invasive sampling techniques, and ethical frameworks is crucial to integrate microbiota monitoring into routine clinical practice for NDDs effectively [59, 60].

Limitations in Gut Microbiota Research for NDDs

Despite the promising potential of gut microbiota in monitoring NDDs, several limitations hinder its clinical application. One major challenge is the complexity and variability of the human microbiome. Individual microbiota profiles can be influenced by numerous factors, including genetics, diet, environment, and medications, making it difficult to pinpoint specific microbial signatures that are universally applicable to NDDs [61]. Additionally, the lack of standardized methodologies for microbiota analysis complicates the comparison of results across studies, leading to inconsistent findings. These factors make it challenging to establish robust, reproducible biomarkers for NDDs based solely on gut microbiota [62].

Another limitation is the current understanding of the mechanisms through which gut microbiota impacts brain development and behavior. While it is clear that gut microbiota influences neuroinflammation, neurotransmitter production, and BBB integrity, the precise molecular pathways remain unclear [63]. More research is needed to determine how specific microbial species, or their metabolites contribute to or mitigate the symptoms of NDDs. Without a deeper understanding of these underlying mechanisms, it will be difficult to develop targeted therapies that harness the gut microbiota in a clinical setting. Additionally, ethical concerns regarding the manipulation of the microbiome, such as through FMT or probiotics, need to be carefully considered, especially in vulnerable populations like children [64].

Future Prospects in Gut Microbiota Research for NDDs

The future of gut microbiota-based monitoring for NDDs lies in advancing our understanding of the gut-brain axis and refining microbiome-targeted therapies (Figure 2). As microbiome research continues to evolve, more sophisticated tools for microbiota profiling, such as metagenomics and metabolomics, are expected to provide deeper insights into the specific microbial species and metabolites that influence neurodevelopmental processes [65, 66]. Additionally, the development of non-invasive diagnostic techniques, such as saliva or breath tests, could make microbiota monitoring more practical and accessible for routine clinical use. By identifying microbial markers that correlate with NDD risk and severity, clinicians may be able to better predict outcomes and tailor interventions to individual patients [67].

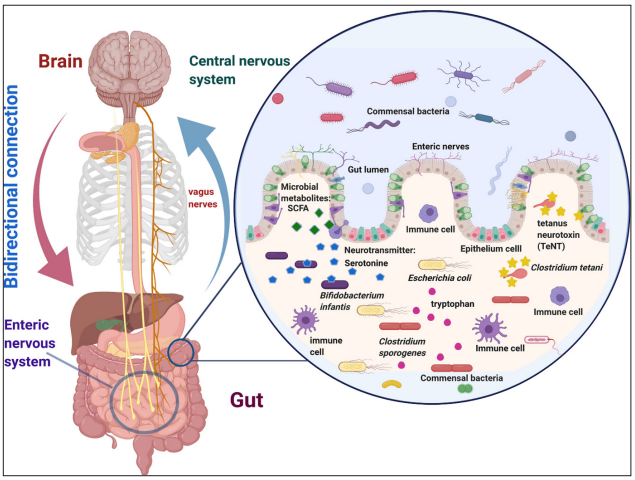


Figure 2: Gut-brain axis [65].

In the coming years, personalized microbiome-based therapies are expected to become a key part of NDD treatment strategies. Advances in probiotic, prebiotic, and dietary interventions, tailored to the unique microbiota profiles of individuals with NDDs, hold great promise for improving clinical outcomes. FMT, which has shown success in certain conditions like *Clostridium difficile* infection, could also be explored as a potential therapy for children with NDDs, although safety and efficacy need to be further validated [68, 69]. Moreover, integrating gut microbiota monitoring with other diagnostic tools, such as genetic testing or neuroimaging, could provide a more comprehensive approach to diagnosing and managing NDDs, ultimately leading to improved patient care and quality of life.

Conclusion

While there are significant challenges in using gut microbiota for monitoring and treating NDDs, the field is rapidly advancing. The potential to develop non-invasive diagnostic tools, personalized microbiota-based therapies, and predictive biomarkers offers hope for better management of NDDs in the future. Continued research into the complex interactions between the gut, microbiota, and brain is essential to overcome current limitations and unlock the full therapeutic potential of the gut-brain axis in NDDs.

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Conflict of Interest

None.

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