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Research Article

EARLY BRAIN DEVELOPMENT FROM PRENATAL STAGE TO AGE TWO: INFLUENCE OF ENVIRONMENTAL FACTORS, CAREGIVER BONDING, AND SOCIAL INTERACTION

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Abstract

This review explores early brain development from the prenatal stage through age two, emphasizing the influence of environmental factors, caregiver bonding, and social interaction on neurodevelopmental outcomes. Drawing on research from neuroscience, developmental psychology, and paediatrics, it examines the dynamic relationship between genetic predispositions and external influences such as maternal nutrition, mental health, socioeconomic status, and exposure to toxins. The review outlines key neurodevelopmental processes, including neural proliferation, synaptogenesis, myelination, and critical periods of plasticity. It further considers how early caregiving environments and social interactions shape emotional regulation and cognitive development. The findings highlight the vital role of responsive caregiving, enriched learning environments, and early interventions in supporting healthy development. The review concludes with recommendations for integrated public health strategies, policy reform, and targeted support for vulnerable populations to promote optimal developmental outcomes in early childhood.

Keywords: Early brain development, Prenatal stageenvironmental factors, Caregiver bonding, Social interaction on neurodevelopmental outcomes.

INTRODUCTION

The first two years of life mark a unique phase of rapid brain development, during which core neural pathways are formed, influencing cognitive, emotional, and behavioral outcomes throughout life. This critical period begins before birth, as genetic and environmental factors interact to shape brain architecture. While genetics set the foundation, factors such as maternal health, nutrition, stress, and the quality of caregiving after birth play a key role in determining the brain's structure and function [1], [2]. During this period, key neurodevelopmental processes such as neural proliferation, synaptogenesis, and myelination take place at a rapid pace, forming the basis for sensory processing, motor skills, language development, and executive functions. However, these processes are highly vulnerable to disruptions, especially from harmful prenatal exposures like poor nutrition, toxins, or high levels of stress. After birth, brain development continues to be shaped by the quality of interactions between caregivers and infants, as well as early social experiences, which affect emotional regulation, secure attachment, and social skills [3]. Because early brain development has long-lasting effects, it is important to understand the biological processes and environmental factors that influence it. This understanding is key to guiding clinical care, educating parents, and shaping effective public health programs [4]. This paper synthesizes current research on prenatal and early postnatal brain development, identifies key protective and risk factors, and offers evidence-based recommendations to support healthy developmental outcomes in young children.

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DISCUSSION

Neurodevelopmental Processes

Early brain development involves several essential biological processes, including neural proliferation, cell migration, differentiation, synaptogenesis, and myelination. Neural proliferation starts as early as the third week of pregnancy and reaches its peak between weeks 8 and 16, generating hundreds of thousands of neurons each minute [5]. These newly formed neurons then travel to their specific destinations in the brain, guided by molecular signals and structural pathways. Synaptogenesis, the creation of connections between neurons, begins before birth and becomes most active during the first two years of life, supporting rapid growth in cognitive and sensory abilities. Myelination occurs next, increasing the speed and efficiency of communication between brain cells. Throughout this developmental period, critical periods, times of increased brain plasticity, emerge. During these windows, environmental experiences have a strong influence on shaping brain structure and function, helping to form the foundation of lifelong learning and behavior [6].

Prenatal Influences

Maternal health and nutrition play a crucial role in fetal brain development. Deficiencies in important nutrients such as folate, iron, iodine, and omega-3 fatty acids have been linked to changes in brain structure and reduced cognitive abilities [7], [8]. On the other hand, exposure to harmful substances like alcohol and nicotine during pregnancy can cause long-lasting neurological problems, including Fetal Alcohol Spectrum Disorders [9]. Maternal mental health also has a significant impact. Chronic stress raises cortisol levels, which can cross the placenta and affect the development of brain areas involved in memory and emotion regulation [10], [11]. Additionally, maternal depression has been connected to decreased gray matter volume and delays in language development in children [12], [13].

Environmental and Social Influences

Socioeconomic status (SES) affects access to proper nutrition, healthcare, and enriching environments, all of which play a vital role in brain development [2]. Children from low-SES families often face developmental delays due to limited cognitive stimulation and higher exposure to environmental hazards like lead and air pollution [14]. These challenges can negatively impact executive functioning and attention skills. Among the most important factors for healthy development is responsive caregiving. Programs such as the Video Interaction Project (VIP) show that structured support can strengthen parent-child interactions and promote better developmental outcomes [14]. Additionally, interactions with peers and siblings help support social and emotional growth by encouraging empathy, cooperation, and conflict resolution skills [15], [16].

Digital Media Exposure

As digital media use rises among infants and toddlers, concerns about its effects on brain development have increased. Excessive screen time before the age of two has been linked to delays in language development and problems with sleep [17], [18]. However, when caregivers watch together with children and the content is educational and high-quality, some of these negative effects may be reduced [19], indicating that digital media can have benefits when used thoughtfully and in moderation [20].

Maternal Health

The physical and mental health of the mother is crucial for the neurodevelopment of the fetus. Medical conditions during pregnancy, such as hypertension, gestational diabetes, or infections, can interfere with placental function and reduce oxygen supply to the fetus, which can hinder the growth and development of neurons [21]. Similarly, maternal mental health issues, particularly anxiety and depression, have been associated with changes in the development of the fetal hypothalamic-pituitary-adrenal (HPA) axis, raising the risk of emotional and cognitive problems in the child later in life [22], [23].

Maternal Nutrition

Proper maternal nutrition is vital for healthy brain development. Lack of important nutrients such as iron, iodine, omega-3 fatty acids, and folic acid has been connected to problems in neuron formation and synapse function. For example, iron deficiency can cause issues with myelination, while folate deficiency is associated with neural tube defects and abnormal brain cortex development [24]. Nutrition before and during pregnancy is a strong predictor of an infant's cognitive and motor skills.

Maternal Stress

Prenatal stress, especially when chronic or intense, raises maternal cortisol levels that pass through the placenta and can affect the developing fetal brain. This can lead to structural changes such as reduced volumes in the hippocampus and prefrontal cortex, areas crucial for memory and executive functions. These stress-related epigenetic changes may have lasting impacts on neuroendocrine regulation and behavior [22], [23].

Environmental Toxins

Exposure to environmental pollutants like air pollution, heavy metals (such as lead and mercury), and pesticides can greatly interfere with brain development. Research has shown that prenatal exposure to fine airborne particles is linked to lower IQ scores and a higher risk of autism spectrum disorders [25], [26]. These neurotoxic substances can disrupt neuron migration and synapse formation, particularly during the second trimester when brain development is at its peak.

Combined Environmental Stressors

These factors often occur together rather than separately. Poor nutrition, chronic stress, and exposure to environmental toxins frequently happen simultaneously, especially in socioeconomically disadvantaged settings. Their combined effects can work together to harm brain development, increasing the risk of attention problems, language delays, and learning disabilities [27], [28]. Public health efforts need to address the combined impact of these multiple risks on fetal brain growth.

POSTNATAL ENVIRONMENTAL STIMULATION AND COGNITIVE GROWTH

The first two years of life are a crucial time for brain development, with over a million neural connections forming every second. During this period, the infant's brain is highly responsive to environmental influences. Experiences after birth, such as sensory stimulation, language exposure, the quality of the surroundings, and socioeconomic factors, play a powerful and lasting role in shaping cognitive and brain development [29].

Sensory Stimulation

Early sensory experiences like touch, sound, light, and movement are essential for developing neural pathways involved in perception, motor skills, and emotional control. Environments rich in sensory stimuli, such as music, different textures, and physical activity, have been shown to support better development of the hippocampus, a brain area important for learning and memory [30].

Language Exposure

Exposure to language, especially through child-directed speech, is a key factor in early brain development and future academic achievement. By 18 months, babies who grow up in language-rich settings typically have much larger vocabularies than those who experience less verbal interaction. The development of brain pathways for language depends on both how much and how well infants are exposed to language [31].

Physical Environment

The quality of the home environment—such as cleanliness, noise levels, and access to age-appropriate toys and books—impacts cognitive, emotional, and motor growth. Safe and engaging surroundings that promote exploration help develop attention, problem-solving abilities, and curiosity [32].

Socioeconomic Factors

Socioeconomic status (SES) plays a major role in determining access to enriching experiences, proper nutrition, and stress management. Children from lower-SES families often face chronic stress and limited cognitive stimulation, which are linked to reduced brain size in regions involved in executive function and language. Nevertheless, caring and responsive parenting can help lessen some of these negative impacts [33].

Combined Effects and Long-Term Implications

Environmental factors often work together, making their combined impact stronger than each factor alone. Children raised in enriched environments, no matter their socioeconomic status, tend to show better executive function and language skills. On the other hand, early deprivation even without clear neglect—can hinder brain development and slow cognitive progress. These early experiences can also influence how brain development unfolds throughout life [34].

THE NEUROSCIENCE OF CAREGIVER BONDING AND ATTACHMENT

Bonding with caregivers and early attachment relationships play a vital role in shaping the developing brain's structure and its ability to regulate emotions. These early connections help form neural networks that manage stress, process emotions, and support social understanding [35].

Secure Attachment as a Neurodevelopmental Foundation

Secure attachment gives infants a feeling of safety and confidence, forming a neurobiological base for exploration and self-control. It supports the growth of the prefrontal cortex, a key brain area involved in executive functions and behavior regulation [36], [37].

Early Attachment and Brain Architecture

Secure attachment encourages synaptic development in brain areas responsible for emotional and social regulation, including the amygdala and anterior cingulate cortex. These changes improve an infant's capacity to handle stress and understand emotional signals [38], [39].

Emotional Attunement and Mirror Neuron Development

Emotionally responsive caregiving stimulates mirror neuron systems that support empathy and social understanding. Through synchronized interactions and shared emotions, the caregiver and infant strengthen neural pathways involved in social cognition [40], [39].

Neurochemical Mechanisms of Attachment

Attachment behaviors result from a complex interaction of neurochemicals [41], [35]:

- Oxytocin promotes bonding, trust, and emotional closeness.
- Dopamine reinforces rewarding social experiences.
- Serotonin helps regulate mood and social ease.
- Elevated cortisol signals stress and can reduce attachment security.
- Endorphins increase feelings of safety and emotional warmth during positive interactions.

Long-Term Effects on Emotional Regulation and Mental Health

Secure early attachment supports emotional resilience, empathy, and stable relationships across the lifespan. Conversely, insecure attachment is linked to a higher risk of internalizing disorders like anxiety and depression and can negatively affect future relationship skills [37], [38].

THE BIOLOGY OF SOCIAL CONNECTION: OXYTOCIN AND MIRROR NEURONS

Social connection is rooted in the biological interplay between oxytocin signaling and mirror neuron activity. This interaction forms the neural and hormonal basis for empathy, attachment, and social bonding [42].

Oxytocin: The Social Bonding Hormone

Oxytocin, produced by the hypothalamus, is released during affectionate touch, childbirth, and bonding experiences. It helps lower social anxiety, build emotional trust, and improve the ability to recognize social signals. Importantly, oxytocin also boosts the activity of the mirror neuron system, enhancing empathy [42].

Mirror Neurons: Neural Basis of Empathy

Mirror neurons fire both during self-initiated action and when observing others. They enable internal simulation of others' experiences, forming the neural substrate of empathy. It is described by [43] as understanding others "from the inside."

Oxytocin Mirror Neurons = Social Empathy

Oxytocin increases the sensitivity of mirror neurons, producing a combined effect that strengthens spontaneous empathy and emotional connection [44].

Early Bonding and Parenting

Oxytocin and mirror neurons work together to regulate the early caregiver-infant bond. Research by [45] demonstrated that these systems form the neurobiological basis for future social abilities. Additionally, [46] found that both maternal and paternal brains exhibit increased mirror neuron activity in response to their own infant, a process influenced by oxytocin release.

Oxytocin in Adult Social Behaviour

In adulthood, oxytocin continues to promote prosocial behaviors such as empathy, intimacy, and cooperation by influencing neural systems responsible for social cognition [47]. The concept of "embodied simulation," introduced by [48], suggests that mirror neurons enable individuals to internally experience the emotions of others.

Empathy as a Universal Biological Capacity

Evidence was reviewed by [49] that empathy arises from universally shared neural structures, such as the mirror neuron system and oxytocin pathways.

Neural Plasticity and Hormonal Modulation

Oxytocin's role in shaping social behaviour is dynamic. It was shown by [50] that changes in oxytocin receptor activity can alter social responsiveness. Furthermore, [51] highlighted that comforting behaviours, such as mutual gaze and hugging, are strongly rooted in neural systems regulated by oxytocin.

SOCIAL INTERACTION AND LANGUAGE DEVELOPMENT IN INFANCY AND TODDLERHOOD

Neural Sensitivity to Language Input in Infants

Infants' neural responses to language are strongly shaped by the context in which it is experienced. A study using event-related potentials (ERPs) [52] showed that 9.5-month-old monolingual English-learning infants could learn new Spanish phonemes after a brief but intensive period of live interaction with native Spanish speakers. Following 12 live Spanish tutoring sessions, the infants demonstrated significant neural gains in distinguishing Spanish phoneme contrasts, an ability they lacked before exposure. Meanwhile, their neural responses to native English phonemes remained unchanged, indicating that the improvement was specific to the new Spanish sounds. This highlights the infant brain's remarkable plasticity and its responsiveness to second-language input, particularly when delivered through socially interactive and engaging experiences.

The Role of Social Interaction in Language Learning

The "social gating hypothesis" [53], [54] provides a convincing explanation for these results: infants show increased attention to language when it is presented in socially interactive contexts. During live interactions, the adult's communicative intent and eye contact motivate infants, making the language input more noticeable and engaging. This is in stark contrast to passive exposure through television or audio, which does not support phonetic learning, even when the content and exposure duration are the same. Live social interactions foster emotional and cognitive engagement, boosting arousal and attention, both essential for effective language acquisition. This explains why infants were unable to learn new phonetic contrasts when exposed to recorded speech without a social presence [55].

Joint Attention and Face-to-Face Communication

Face-to-face interaction boosts joint attention, which is crucial for infant language learning. When an adult and infant focus on the same object or event and the adult offers verbal labels, the infant is more likely to connect words with their meanings. These joint attention moments help organize learning experiences and support the growth of vocabulary and pragmatic language skills. Moreover, contingent verbal engagement where adults respond quickly and meaningfully to infants' vocalizations enhances speech processing abilities. These social interactions provide a framework that assists infants in segmenting speech into meaningful phonetic units [56].

Implications for Early Language Intervention

These findings highlight the critical role of socially responsive, interactive environments in early language learning. Interventions focusing on active human interaction, rather than passive media exposure, are more likely to effectively support the development of both first and second languages during infancy and toddlerhood. Especially in bilingual contexts, prioritizing live engagement with caregivers or tutors can best leverage the brain's early sensitivity to phonetic cues [56].

CULTURAL VARIATIONS IN CAREGIVING AND SOCIAL INTERACTION IN EARLY CHILDHOOD

Early childhood development is deeply influenced by cultural contexts that shape caregiving practices and social interaction norms. As noted by [57], cultural values affect not only how caregivers engage with children but also the developmental goals they prioritize. In individualistic societies, such as the United States and many Western European countries, caregiving often emphasizes independence, autonomy, and verbal expressiveness. Children are encouraged to make choices, express preferences, and participate in open dialogue with adults. In contrast, collectivist cultures common in many parts of Asia, Africa, and the Middle East, value interdependence, respect for authority, and group harmony. Caregiving in these contexts often involves directive communication and behavioral modeling, focusing on obedience, emotional restraint, and fulfilling social roles. These differing interaction styles shape children's socialization outcomes: children from individualistic cultures may develop stronger self-regulation and verbal skills, while those from collectivist cultures tend to show greater social compliance and emotional control. Importantly, these differences do not imply that one cultural model is superior to another. Instead, they reflect how child development adapts to align with the specific values and expectations of each society. Parenting beliefs and behaviors vary across cultures in meaningful ways that influence children's growth. Understanding these differences is crucial for designing culturally sensitive parenting programs and educational policies [57].

ADVERSE CHILDHOOD EXPERIENCES AND THEIR IMPACT ON BRAIN DEVELOPMENT

The Neurodevelopmental Impact of Adverse Childhood Experiences (ACEs)

Adverse childhood experiences (ACEs), such as physical and sexual abuse, neglect, and chronic stress, are consistently linked to lasting neurobiological changes that affect emotional, behavioral, and cognitive functioning throughout life. Evidence from epidemiological and neuroimaging research indicates that ACEs interfere with the development of brain areas essential for emotion regulation and stress response, especially the amygdala, hippocampus, and anterior cingulate cortex (ACC). These effects manifest both functionally, as altered patterns of neural activity, and structurally, including reduced brain volumes and dendritic shrinkage in these regions. Notably, the hippocampus shows volume reductions proportional to the cumulative burden of ACEs exposure [58].

Dose-Dependent and Timing Effects on Brain Morphology

Research shows a dose–response relationship: as the number and severity of ACEs increase, the neurobiological changes become more pronounced. This supports a cumulative risk model, where repeated or multiple adversities result in progressively greater neural and behavioral impairments. Moreover, the timing and type of ACEs play a crucial role in determining outcomes. Stress experienced during sensitive developmental periods tends to have more harmful effects on brain plasticity. For instance, early neglect impacts hippocampal development, whereas abuse occurring later may more strongly affect amygdala responsiveness to threats [59].

Mechanisms of Stress Neurotoxicity

The biological mechanism driving these changes is closely associated with glucocorticoid neurotoxicity. Brain areas like the hippocampus and anterior cingulate cortex (ACC) have a high concentration of glucocorticoid receptors, making them especially vulnerable to prolonged stress and cortisol imbalance. Continuous exposure to stress hormones results in [59]:

- Reduced neurogenesis
- Dendritic retraction
- Synaptic loss
- Impaired connectivity between prefrontal-limbic circuits

These changes impair the brain's ability to regulate affect, respond to stress adaptively, and support cognitive functions such as memory and executive control.

Long-Term Behavioral and Psychosocial Outcomes

The neurobiological effects of adverse childhood experiences (ACEs) lead to greater emotional dysregulation, cognitive impairments, and an elevated risk for psychiatric conditions such as anxiety, depression, PTSD, and substance abuse. Functional MRI research shows increased attentional bias toward threat-related stimuli and heightened amygdala reactivity, which contribute to hypervigilance and challenges in social interactions. Behaviorally, individuals who have experienced ACEs frequently struggle with social functioning, learning, and self-regulation, difficulties that often continue into adulthood and perpetuate cycles of trauma across generations [60].

Implications for Intervention and Resilience

Recognizing the neural impact of adverse childhood experiences (ACEs) opens the door to early detection and trauma-informed treatment approaches. Proven therapies, including trauma-focused cognitive-behavioral therapy (CBT) and attachment-based interventions, can support neuroplasticity and enhance emotional and cognitive outcomes for those affected. Furthermore, nurturing and supportive caregiving early in life can help counteract the negative neurodevelopmental effects of ACEs, highlighting the importance of prevention strategies within healthcare and education systems [61].

INTERVENTIONS AND SUPPORT SYSTEMS FOR OPTIMAL DEVELOPMENT

Importance of Responsive Parenting in Early Childhood Development

Parents play a pivotal role in shaping a child's early development. Responsive caregiving—characterized by consistent, sensitive, and timely reactions to a child's needs—is crucial for healthy brain growth, particularly within the first three years. Through early stimulation, emotional safety, and nurturing interactions, this caregiving fosters neurocognitive, language, and motor skills, laying the groundwork for lifelong learning and overall well-being [4].

Global Effectiveness of Parenting Interventions

The systematic review and meta-analysis conducted by [4], encompassing 102 studies from 33 countries, revealed that parenting interventions significantly enhance early childhood outcomes. Key insights include:

- Greater improvements in cognitive, language, and motor development were observed in low- and middle-income countries (LMICs) compared to high-income countries (HICs).
- Specifically, the impact on cognitive development in LMICs was three times higher than that in HICs.
- Programs focused on responsive caregiving yielded notably better results in:
    - Child cognitive development
    - Parenting knowledge and practices
    - The quality of parent–child interactions

These results highlight the importance of context in the effectiveness of parenting support and indicate that interventions have the greatest impact when customized to the developmental and socioeconomic conditions of each region.

Responsive Caregiving as a Core Intervention Component

Interventions that specifically focused on responsive caregiving behaviors such as recognizing infant cues, fostering emotional attunement, and encouraging stimulating play showed greater improvements in both child development and parenting quality. These programs take advantage of critical sensitive periods in early brain development, strengthening neural pathways involved in emotional regulation, language learning, and executive functioning [4].

Synthesis of Key Findings

The supporting literature highlights several interconnected factors that influence early brain development:

Neural proliferation begins as early as the third week of pregnancy and peaks between weeks 8 and 16 [5]. However, disruptions such as maternal nutrient deficiencies or exposure to harmful substances like alcohol and nicotine can have lasting neurological consequences, including structural brain changes and impaired cognitive function [7]–[9]. Maternal health and mental well-being significantly affect fetal brain growth through mechanisms such as placental function, nutrient transfer, and hormonal signaling. Chronic stress elevates cortisol levels that cross the placenta, altering the development of emotion-regulating brain regions like the hippocampus and prefrontal cortex [10]–[13], [22], [23]. Secure attachment plays a foundational role in emotional regulation and social competence. Responsive caregiving promotes growth in brain regions such as the prefrontal cortex, amygdala, and anterior cingulate cortex [35]–[39]. The release of oxytocin, dopamine, and serotonin reinforces bonding, while mirror neuron activity supports empathy and social understanding [41]–[47]. Language acquisition is deeply rooted in live, emotionally engaging interactions. Research confirms that infants learn phonemes most effectively through face-to-face communication rather than passive media exposure [52]–[56], highlighting the irreplaceable value of human connection in early language development. Environmental influences, including pollution, toxins, and socioeconomic conditions, can have lasting effects on brain development [25], [26]. Enriched environments foster attention, problem-solving, and language development, while deprivation even without overt neglect can slow cognitive progress [34]. Adverse childhood experiences (ACEs) such as abuse, neglect, and chronic stress have profound neurobiological consequences. These experiences disrupt emotion-regulating brain structures, leading to reduced hippocampal volume, heightened amygdala reactivity, and impaired connectivity between prefrontal-limbic circuits [58]–[60].

Strengths and Limitations

A key strength of this review is its interdisciplinary synthesis of findings from neuroscience, psychology, paediatrics, public health, and anthropology. Advances in neuroimaging, hormonal biomarker analysis, and longitudinal cohort studies have enabled researchers to identify associations and, in some cases, potential causal pathwaysbetween early environmental exposures and long-term developmental outcomes. Despite these strengths, several methodological and contextual limitations are evident:

- Most existing studies employ correlational or observational designs, which limit the ability to establish causality.
- Longitudinal neuroimaging studies that follow individuals from infancy through adulthood remain scarce, limiting our understanding of how early brain changes translate into later cognitive and behavioral outcomes.
- Most research has been conducted in Western, high-income settings, significantly constraining the generalizability of findings across diverse cultural and socioeconomic contexts.

Identified Gaps in Knowledge

Several important knowledge gaps remain in our understanding of early brain development and its modulation by environmental influences:

1. **Need for Longitudinal and Life course Research:** There is a critical need for long-term, diverse cohort studies that follow children from the prenatal period through adolescence and beyond. Such research would clarify how early-life exposuresboth protective and harmfulaffect long-term neurocognitive, emotional, and behavioral outcomes.
2. **Culturally Relevant and Context-Specific Interventions:** While many early childhood programs show promise, few are designed with cultural adaptation in mind. There is a growing need to develop and evaluate locally relevant, context-sensitive interventions—particularly in low- and middle-income countries—to improve program uptake, engagement, and effectiveness.
3. **Understanding Environmental Influences Through Epigenetics:** Emerging evidence suggests that environmental stressors (e.g., maternal stress, pollution, poor nutrition) may exert their effects via epigenetic mechanisms. However, comprehensive, mechanistic human studies that link environmental exposures to gene expression and neural outcomes are limited and urgently needed.
4. **Diversifying Study Populations:** A significant proportion of current research focuses on Western, Educated, Industrialized, Rich, and Democratic (WEIRD) populations, leading to a skewed understanding of typical and atypical development. Expanding research to include underrepresented groups across different geographic, ethnic, and socioeconomic backgrounds is essential for building a globally representative science of early brain development.
5. **Early Detection and Scalable Interventions:** There is a pressing need for accessible, cost-effective tools to detect developmental risk early and deliver timely, targeted interventions. Low-resource settings require scalable, community-based solutions that can identify and support vulnerable infants and toddlers before developmental delays become entrenched.

Addressing these gaps demands interdisciplinary collaboration across neuroscience, public health, genetics, anthropology, and education. Prioritizing longitudinal, inclusive, and mechanistic research will deepen our understanding of early brain development and enable the design of equitable, evidence-based interventions that promote optimal neurodevelopment across diverse populations.

Recommendations and Implications for Policy and Practice

To support optimal early brain development from the prenatal stage through age two, a multifaceted, interdisciplinary approach is essential. Based on the synthesis of current evidence, the following recommendations are organized into six key domains: maternal and preconception health, environmental protection, parenting and caregiving, early learning and stimulation, research priorities, and system-level investments.

1. **Maternal and Preconception Health:**

- Integrate maternal mental health screening and support into routine prenatal care, with targeted interventions for stress, depression, and anxiety.
- Promote nutritional counseling and supplementation with essential micronutrients such as folic acid, iron, iodine, and

omega-3 fatty acids during both preconception and pregnancy.
- Expand access to preconception health assessments that include nutritional status, psychological readiness, and reproductive planning to optimize fetal neurodevelopmental outcomes.

2. Environmental Risk Reduction

- Strengthen policies to reduce exposure to neurotoxins such as lead, mercury, and air pollutants, particularly in low-income and vulnerable communities.
- Incorporate environmental risk monitoring into standard paediatric and prenatal healthcare practices to identify and mitigate early developmental threats.
- Raise public awareness about the risks of environmental toxins and promote safer alternatives in housing, food, and consumer products.

3. Responsive Parenting and Caregiving

- Scale up evidence-based parenting programs such as home visiting services and Video Interaction Project (VIP) especially in low- and middle-income countries.
- Prioritize responsive caregiving curricula within early childhood frameworks to enhance parent-child interactions, emotional attunement, and language-rich environments.
- Support parental mental health and social protection programs to improve program uptake and effectiveness, particularly among at-risk populations.
- Promote intentional, balanced, and developmentally informed parenting during the first few years, recognizing the long-term impact of early caregiving on brain architecture and emotional regulation.

4. Early Learning, Stimulation, and Media Use

- Encourage rich sensory experiences through touch, movement, and nature-based exploration, especially during infancy, to support the maturation of sensory neural circuits.
- Provide safe opportunities for free exploration beginning in the second half of the first year to foster curiosity, sensory integration, and emotional resilience.
- Limit screen exposure before age two and discourage passive media use. When digital tools are used, emphasize co-viewing, interactivity, and educational content.
- Use age-appropriate storytelling and play to stimulate language acquisition, cognitive growth, and socioemotional development.
- Monitor auditory and visual input quality, ensuring that infants receive meaningful, developmentally appropriate stimuli while being protected from overstimulation or sensory deprivation.

5. Cultural Sensitivity and Trauma-Informed Approaches

- Adapt parenting and intervention programs to reflect cultural values and child-rearing norms, ensuring relevance and acceptability across diverse populations.
- Implement trauma-informed approaches for children exposed to adverse childhood experiences (ACEs), integrating these into healthcare, education, and child protection systems.

6. Research Priorities and System-Level Investment

- Prioritize longitudinal studies examining cumulative environmental risk, epigenetic mechanisms linking maternal stress to child outcomes, and the long-term effects of early interventions.
- Invest in scalable early intervention systems that integrate maternal, child, and family support within existing community health infrastructures.
- Recognize the high return on investment in early neurodevelopment, with benefits extending to public health, education, economic productivity, and lifelong well-being.

Conclusion

The period from conception to age two represents a critical window of brain development, shaped by the dynamic interplay of biological, environmental, and relational factors. From prenatal neural proliferation to postnatal synaptogenesis, this stage lays the foundation for lifelong cognitive, emotional, and behavioral health. Maternal health, nutrition, and mental well-being significantly influence fetal neurodevelopment, while responsive caregiving, enriched environments, and meaningful social interactions drive postnatal growth. Adverse childhood experiences, environmental toxins, and inappropriate media exposure pose serious risks, with long-term consequences for brain structure and function. Cultural contexts further shape developmental pathways, emphasizing the need for tailored, context-sensitive interventions. Evidence-based strategies ranging from maternal nutritional supplementation and mental health support to early parenting programs and sensory-enriched learning—offer promising avenues to promote healthy development and mitigate risk. Investment in early neurodevelopment yields high returns across sectors, including public health, education, and economic productivity. In sum, early brain development is not solely a biological processit is deeply influenced by the world into which a child is born. By aligning science, policy, and practice, we can create nurturing environments that maximize human potential and foster resilient, equitable societies.

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