

# Sensory Development in the Fetus, Neonate, and Infant: Introduction and Overview

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The knowledge and understanding of the development of the sensory systems in the fetus, neonate, and infant have progressed and grown extensively in the past twenty to thirty years. This has been a result of the advances in technology for study of brain development and the sensory systems specifically. While the basic physical structure of the sensory receptors (i.e. eyes, ears etc.) develops early in gestation, most of the neurosensory development occurs in the last sixteen to twenty weeks. The neurological processes are not accelerated by preterm birth. Preterm birth accelerates the maturation of the kidney, gastrointestinal, lung and cardiovascular function but does not alter the sequence or timing of neurodevelopment. The stresses and the environment of the Newborn Intensive Care Unit (NICU) play a major role in the altered neurodevelopment observed in preterm infants. The brain development in the fetus, neonate, and infant includes not just sensory systems but motor systems, social/emotional systems, and the cognitive systems. These systems are connected and integrated during development. The development of the brain, both structure and function, is shaped by the influence of four major factors or processes. These include (1) the genetic endowment and the epigenetic effects from the environment, (2) the endogenous or internal brain activity and sleep, (3) external experiences and stimulation of the sensory organs, and (4) the physical, chemical, sensory, and social/emotional environments. These factors operate on and influence the development of each of the brain systems. These effects depend on age and developmental level of the particular system. Many of the processes and stimulations needed to facilitate brain development can result in adverse effects if exposure is at the wrong time in development or the level of intensity is not appropriate. The NICU environment can have very adverse consequences for healthy neurodevelopment. It is essential that the environment of the fetus, neonate, infant be adapted and managed to provide for the healthy early brain development. This requires both a developmentally, supportive environment and developmentally appropriate care practices.

**Keywords:** Genetic endowment; Epigenetics; Endogenous brain activity; Rapid eye movement sleep; Physical environment; Chemical environment; Social-emotional environment; Sensory environment; Individualized development care

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Advances in technology and methods for assessing brain function and neurological processes have resulted in greater understanding of the factors involved in early brain development and, in particular, development of the sensory systems.

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Although development of vision and visual systems received the most attention in the 1970s and 1980s, there has been marked progress in understanding the processes of auditory development, touch, chemosensory (smell and taste), kinesthetic, proprioception, and, more recently, the limbic system (emotional learning) and the hippocampus (memory formation). Each of the sensory systems has its own sequence and timing of events, which are critical in the creation of the basic neural architecture of each system. The sensory systems also develop in a sequence, which if altered results in developmental alteration and interference. The sensory systems develop in close association with each other because many aspects of sensory stimulation require coordination or integration to function optimally.

The basic structure of the eyes, ears, and olfactory bulb (smell) develops early in gestation. In addition, some of the primary receptors for touch, position, and motion detection

develop early in gestation. The building of the basic or initial neural architecture of each sensory system occurs in the last 15 to 18 weeks of fetal life (22 to 40 weeks gestational age) and the first 3 to 5 months of neonatal life. The sequence of neurosensory development and the critical events in the process are not significantly altered by preterm birth. The processes proceed whether in utero or in the newborn intensive care unit (NICU). The timing of events is sequenced according to the developmental maturation or developmental age of the fetus or infant. Preterm birth does not accelerate any of the early sensory development processes but can retard or interfere with the sensory development when exposed to stimuli, which are of intense, unusual character, or out of order in the genetically coded sequence. The physical, sensory, and social environment of the fetus, infant, and young child are of critical importance in supporting healthy appropriate development of the brain and neurosensory systems.

Preterm birth accelerates the maturation of kidney function, gastrointestinal function, and lung function but does not accelerate the development of brain function and may delay some of the early brain processes. Preterm birth delays the myelination of the central nerve pathways. The cause of this delay is not known. Infants in the NICU are exposed to many stimuli, which would not occur in utero. The fetus in utero is protected from exposure to high-pitched sound by the absorption of the sound in the tissues and fluid around the fetus as opposed to the preterm infant who is exposed to frequent, high-pitched sound in the NICU. While in the NICU, the infant receives frequent exposure to stress and the stress hormones and less exposure to the calming hormone, oxytocin. Some mothers' lives are also so stressful during pregnancy that their fetuses in utero also reflect the stress with more production of stress hormones and less oxytocin.

Brain development in the fetus (preterm infant) and neonate includes sensory systems, motor systems, social/emotional systems, and cognitive systems. All of these systems are connected and integrated throughout late fetal and early neonatal life. These systems do not develop in isolation. All exogenous or outside sensory stimulation has an emotional component as well as the sensory component. Many sensory stimuli also have social or motor components integrated into the sensory recognition and response. As the sensory systems mature in the last 8 to 10 weeks of fetal life, fetal and neonatal learning begins.

The development of the brain, both structure and function, is shaped by the influence and interaction of four major factors. They include the following:

1. *Genetic endowment.* The brain architecture, cell differentiation, cell migration, primary or initial cell location, and response to initial stimulation are directed by the genes or genetic endowment. However, the expression or effect of a given gene is often influenced or altered by the environment and outside stimulation. Timing, intensity, and type of stimulation from the environment can modify gene expression and become important factors in understanding their effects on early development. All brain

development processes are the result of both nature (genes) and nurture (experience and use).

Factors and stimuli from the physical, chemical, sensory, and social/emotional environment of the fetus or infant can alter the expression of individual genes without altering the basic structure of the DNA. The process of altering gene expression or gene effect is called epigenetics. It is a rapidly expanding field of genetic and developmental research. This can not only affect the gene expression in the fetus or neonate, but in the female fetus or infant, it can also alter the gene expression in the eggs in the ovary, which will alter the development of the next generation. There are now clear examples in the grandchildren of the mother who was initially exposed. The exposure of women to diethylstilbestrol has resulted in developmental changes in their daughters and granddaughters. An entire issue of *Pediatric Research* was recently devoted to the subject of epigenetics.<sup>1</sup>

2. *Internal or endogenous stimulation and sleep.* As part of fetal neurodevelopment, there is spontaneous brain activity that occurs in the absence of outside stimulation. It is genetically programmed into ganglion cells of the sensory and motor systems. It occurs primarily during the last 20 weeks of the gestational life. The spontaneous or endogenous firing of sensory and motor ganglion cells or neurons is essential for axon growth and targeting. The firing of the ganglion cells is initially random but becomes regular with maturation of the sensory organs (eye, ear, and so on). The neurons of the retina, cochlea, spinal cord, and olfactory and limbic systems mature to a level where they fire in synchronous waves beginning around 28 weeks gestation when cycles begin. The synchronous waves only occur during rapid eye movement (REM) sleep. These synchronous waves of stimulus cause the synapses of the sensory system to form permanent connections and circuits that are the basic architecture of the sensory nuclei and neocortex. The endogenous firing of sensory ganglion cells or neurons before 20 weeks gestation is spontaneous, and after 27 to 28 weeks gestation, it is associated with REM sleep.<sup>2-4</sup> Events and drugs that interfere with REM sleep also interfere with development of the basic architecture of the sensory systems as well as the systems associated with emotional and social development. Sleep is essential for the development of the early structural architecture of these systems. It is also necessary for long-term memory and the maintenance of long-term brain plasticity, which is vital to future learning. Sleep is required for neurosensory and cortical development well beyond fetal and neonatal life. It is during REM sleep that the ganglion cells of the retina, cochlea (ear), spinal cord, nuclei of the brain stem, and thalamus first fire in the synchronous waves essential for sensory development. Rapid eye movement sleep deprivation interferes with the development of the basic neural architecture of the sensory system.

3. *External experiences and stimulation of the sensory organs.* With each sensory system, the initial stimulation is

internal or endogenous, but at a critical or sensitive point in development, outside stimulation and experience are needed for further development. The outside stimulation of the sensory systems must occur in appropriate sequence, intensity, and form. When timing, intensity, or form of the stimulation is inappropriate, it will result in interference with the expected development. All of the sensory systems, except vision, need outside or exogenous stimulation as part of development in utero. The human visual system needs synchronous waves of retinal ganglion cell firing in utero but does not need light or vision. Vision becomes essential at or near term.

4. *The environment.* There are four components of the environment that influence fetal, infant, and child development. These are the physical, chemical, sensory, and social/emotional environments. Events and stimuli from each of the four environments are capable of altering the course and outcome of developmental processes. The environments of the fetus, infant and young child can have both positive and negative effects.

The physical environment involves space and characteristics of the space, which affect position, movement, motor development, and the ability to move.

The chemical environment includes nutrition, nutritional factors, and toxic exposures. The factors from the chemical environment (nutrition and toxins) are most likely to create not only direct effects on the fetus or infant but also the epigenetic effects that alter gene expression.

The sensory environment includes the exposures to and experiencing of sound, voice, touch, movement, smell, and vision. These are processes that are critical for neurosensory development. The sensory environment also includes protection of sleep and sleep cycles, which are essential for neurosensory development, memory, learning and long-term brain synapses/circuits, and preservation of brain plasticity for continued learning and development over the life of the individual. They start in fetal life.

The social/emotional environment attaches social and emotional characteristics to sensory stimuli, which create memory circuits in the limbic system (emotional development) and the social learning centers. These social/emotional stimuli associated with touch, smell, hearing, and vision, in addition to the cortical changes, have direct effects in the areas of social and emotional learning and memory. All sensory stimuli carry social and emotional connections and characteristics.

Adverse environmental factors can significantly interfere with health and appropriate neurodevelopment and neuroprocessing. Many environmental insults can result in lifelong alterations in brain development and function.

Each of the individual sensory systems has a sequence and time for the events or stages in development to occur. The timing of events is referred to as critical or sensitive periods. Many of the critical periods of early human sensory development occur while the infant is in the NICU or other care facility.

Events, stimuli, and environmental factors can support the processes of sensory development or create significant interference. Sensory interference and events associated with neurosensory wiring disorders are increasing in frequency and may contribute to some of the adverse outcomes reported in the long-term follow-up of high-risk infants.

Major efforts and programs have focused on changing the environment and care practices in the NICU for over 30 years. In the early 1980s, the physical and developmental environment of the high-risk infants was started. Robert White had the first conference of NICU design. A.W. Gottfried<sup>5</sup> published the book *Infant Stress Under Intensive Care*, emphasizing the new field of "environmental neonatology," and a developmental nursery was established at The University of Missouri.<sup>6</sup> A group of researchers led by Heidelise Als, Gretchen Lawhon, and others developed a program in the early 1980s, which has changed the face of developmental care both in the United States and internationally.<sup>7</sup> The Newborn Individualized Developmental Care and Assessment Program provides for individualized assessment, identification of the infant's developmental goal strivings, and recommends appropriate interventions for the fragile newborn. Newborn Individualized Developmental Care and Assessment Program's emphasis on provision of integrated, well-timed, and carefully planned multisensory experiences, including environmental modifications, has provided the most comprehensive, evidence-based approach to developmentally supportive caregiving to date.<sup>8-12</sup>

Ongoing basic and applied neurobiological and behavioral research contributes to our understanding of the impact of early environments on the developing fetus, neonate, and infant. Careful evaluation of how this information can be used to create environments that both protect and support their development is a challenge for all professionals who work to promote better outcomes for fragile neonates and young infants and their families. Responsible application of principles of developmental neurobiology and psychology to the applied setting of the NICU is not only challenging but also imperative.

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