Published in final edited form as:
Zero Three. 2009 November 1; 30(2): 9–13.

Brain Development and the Role of Experience in the Early Years

Adrienne L. Tierney and
Harvard Graduate School of Education

Charles A. Nelson III
Children's Hospital Boston Harvard Medical School

Abstract

Research over the past several decades has provided insight into the processes that govern early brain development and how those processes contribute to behavior. In the following article, we provide an overview of early brain development beginning with a summary of the prenatal period. We then turn to postnatal development and examine how brain functions are built and how experience mediates this process. Specifically, we discuss findings from research on speech and on face processing. The results of this research highlight how the first few years of life are a particularly important period of development of the brain.

The past 30 years of research have provided a new and deeper understanding of the brain and its role in psychological functions. In particular, researchers now have a better sense of how brain development affects the development of behavior. Measurement techniques such as electroencephalogram (EEG) and event related potentials (ERP) can be used to study infants, children, and adults, and this flexibility has allowed researchers to investigate a variety of developmental processes.

Research using these measures on the developing brain has clarified several arguments about the nature of child development and informed debates such as those surrounding the state of the infant's brain at birth (whether it is a "blank slate" or not), the identification of critical periods of development, and the relative importance of genes versus environment.

It is important to note that, although much of the research has been conducted on infants, it is a collaborative effort between infant and animal research that has uncovered the neurobiological principles that govern development in humans. Researchers have made use of the homology that exists among developing nervous systems of different species, and many of the cutting-edge ideas discussed in the developmental literature have their origins in animal research—but they have been tested and clarified in neurobehavioral experiments with infants and young children. In humans, researchers can investigate the neural correlates of behavior whereas in animals they can dig deeper into the mechanisms that drive the processes that these neural correlates reflect. To this end, much of human brain research in the past three decades has focused on the brain basis of behavior. A more recent a focus on

---

Adrienne L. Tierney, MSc, EdM, is a doctoral student in human development at the Harvard Graduate School of Education. She has a background in neuroscience and is currently involved in the Mind, Brain, and Education program. Her dissertation research is on brain development in children with autism.

Charles A. Nelson III, PhD, is a professor of pediatrics and neuroscience at Harvard Medical School and the Richard David Scott Chair in Pediatric Developmental Medicine Research at Children's Hospital Boston. A developmental cognitive neuroscientist, Nelson's interests lie broadly with how experience influences brain development, with a particular interest in the processing of faces and facial expressions. He has conducted research on typically developing infants and children and children who have experienced early biological and psychosocial adversity.

experience has helped refine researchers' understanding of how developmental processes are fueled.

In the following paragraphs, we will examine some of the essential ideas that have helped researchers understand the development of the human brain in the early years of life. We begin with an overview of the stages involved in the anatomical development of the brain. Subsequently, we examine three topics that research in brain development has uncovered, clarified, and elaborated: how development is hierarchically structured, such that later development depends on early development; how experience in the first year of life modulates the plasticity of the brain; and how early deprivation has strong and lasting effects on the brain.

Early Stages of Brain Development

An account of brain development in the early years of childhood is only complete if we first examine the origins of this process during the prenatal months. Brain development is a protracted process that begins about 2 weeks after conception and continues into young adulthood 20 years later. Brain development that occurs during the prenatal months is largely under genetic control, although clearly the environment can play a role; for example, it is well known that the lack of nutrition (e.g., folic acid) and the presence of toxins (e.g., alcohol) can both deleteriously influence the developing brain. In contrast, much of brain development that occurs postnatally is experience-dependent and defined by gene–environment interactions. Below we provide brief descriptions of the anatomical changes that characterize the early stages of brain development.

Neurulation

About 2 weeks after conception, the developing embryo has organized itself into a three-layered, spherical structure. In one area of this sphere, the cells thicken to form what is called the *neural plate*. This plate then folds over onto itself, forming a tube that gradually closes first at the bottom and then at the top, much like a zipper. This creates the neural tube, the inner cells of which will lead to the formation of the central nervous system (brain and spinal cord) while the outer cells will give rise to the autonomic nervous system (nerves outside the brain and spinal cord).

Once the neural tube is closed, it becomes a three-vesicle structure and shortly thereafter a five-vesicle structure. The different regions of tissue around the ventricles will become distinct brain structures. The anterior portion of the tube will become the *forebrain*, which includes the cerebral hemispheres; the *diencephalon* (the thalamus and the hypothalamus); and the basal ganglia. The cells around the middle vesicle will become the *midbrain*, a structure that connects the diencephalon to the hindbrain. The rear-most portion of the tube will give rise to the *hindbrain*, which will consist of the medulla oblongata, the pons, and the cerebellum. Finally, the cells that remain will give rise to the spinal cord.

Proliferation

Once the general structure of the neural tube has been laid out, the cells that line the innermost part of the tube, called the *ventricular zone*, proliferate at a logarithmic rate. As these cells multiply, they form a second zone, the *marginal zone*, which will contain axons and dendrites. This proliferative stage continues for some time, with the consequence that the newborn brain will have many more neurons than the adult brain. The overproduction of neurons is eventually balanced by a process of *apoptosis*, or programmed cell death. Apoptosis is responsible for a decrease in the cell numbers to adult levels and is completely under genetic control.

Cell migration

After the cells are born, they travel to their final destinations. The cerebral cortex is composed of multilayered tissue several millimeters thick. It is formed by the movement of cells in an inside-out direction, beginning in the ventricular zone and migrating through the intermediate zone, with the cells eventually reaching their final destination on the outside of the developing brain. The earliest migrating cells occupy the deepest cortical layer, whereas the subsequent migrations pass through previously formed layers to form the outer layers. About 25 weeks after conception, all six layers of the cortex will have formed.

The inside-out pattern of migration described here is that of *radial migration*, which applies to about 70%–80% of migrating neurons, most of which are pyramidal neurons and glia. *Pyramidal neurons* are the large neurons in the cortex that are responsible for sending signals to different layers of the cortex and other parts of the brain. *Glia* are nonneuronal brain cells that are involved in the support of neuronal processes (such as producing myelin or removing debris, such as dead brain cells). In contrast, *interneurons*—relatively smaller neurons that are involved in communication between pyramidal cells within a particular layer of the cortex—follow a pattern of tangential migration.

Differentiation

Once a neuron has migrated to its target destination, it generally proceeds along one of two roads: It can differentiate into a mature neuron, complete with axons and dendrites, or it can be retracted through apoptosis. Current estimates suggest that the number of neurons that are retracted is between 40% and 60% (see Oppenheim & Johnson, 2003). The development of axons is facilitated by *growth cones*, small structures that form at the edge of an axon. The cellular processes that occur at the growth cone promote growth toward certain targets and away from others. Such processes are driven by molecular guidance cues as well as by anatomic structures at the tip of the growth cone.

Dendrite formation occurs by a slightly different process, one that is thought to be driven by genes controlling calcium-regulated transcription factors (Aizawa et al., 2004). Early dendrites appear as thick strands with few spines (small protuberances) that extend from the cell body. As dendrites mature, the number and density of spines increases, which in turn increases the chances that a dendrite will make contact with a neighboring axon. Connections between dendrites and axons are the basis for synaptic connections between neurons, which, as we will describe below, is essential for brain function.

Synaptogenesis

A *synapse* is a point of contact between two brain cells, often two neurons and frequently a dendrite and an axon. The first synapses are generally observed by about the 23rd week of gestation (Molliver, Kostovic, & Van der Loos, 1973), although the peak of production does not occur until some time in the first year of life. As is the case with neurons, massive overproduction of synapses is followed by a gradual reduction. This process of synapse reduction, or *pruning*, is highly dependent on experience and serves as the basis of much of the learning that occurs during the early years of life. It is important to note that the various structures of the brain reach their peak of synapse production at different points. In the visual cortex, for example, the peak is reached somewhere between the 4th and 8th postnatal month, but areas of the prefrontal cortex do not reach their peak until the 15th postnatal month. The difference in timing in peak synapse production is important because it affects the timing of the plasticity of these regions; the later the peak synapse production, the longer the region remains plastic.

Synapse pruning

The overproduction of synapses is followed by a pruning back of the unused and overabundance of synapses. Until the stage of synaptogenesis, the stages of brain development are largely gene driven. However, once the brain reaches the point where synapses are eliminated, the balance shifts; the process of pruning is largely experience driven. As with synapse production, the timing of synapse pruning is dependent on the area of the brain in which it occurs. In the parts of the cortex involved in visual and auditory perception, for example, pruning is complete between the 4th and 6th year of life. In contrast, pruning in areas involved in higher cognitive functions (such as inhibitory control and emotion regulation) continues through adolescence (Huttenlocher & Dabholkar, 1997). The processes of overproduction of synapses and subsequent synaptic reduction are essential for the flexibility required for the adaptive capabilities of the developing mind. It allows the individual to respond to the unique environment in which he or she is born. Those pathways that are activated by the environment are strengthened while the ones that go unused are eliminated. In this way, the networks of neurons involved in the development of behavior are fine-tuned and modified as needed.

Myelination

The final process involved in the development of the brain is called *myelination*. In this process the axons of neurons are wrapped in fatty cells, which ultimately facilitates neuronal activity and communication because this insulation allows myelinated axons to transmit electrical signals faster than unmyelinated axons. The timing of myelination is dependent on the region of the brain in which it occurs. Regions of the brain in certain sensory and motor areas are myelinated earlier in a process that is complete around the preschool period. In contrast, regions involved in higher cognitive abilities, such as the prefrontal cortex, the process is not complete until adolescence or early adulthood (for recent reviews see Nelson, de Haan, & Thomas, 2006; Nelson & Jeste, 2008).

Summary

In general, brain development begins a few weeks after conception and is thought to be complete by early adulthood. The basic structure of the brain is laid down primarily during the prenatal period and early childhood, and the formation and refinement of neural networks continues over the long term. The brains' many functions do not develop at the same time nor do their developmental patterns follow the same time frame. Although basic sensation and perception systems are fully developed by the time children reach kindergarten age, other systems such as those involved in memory, decision making, and emotion continue to develop well into childhood. The foundations of many of these abilities, however, are constructed during the early years.

The principles of anatomical change described above are essential to the maturation and development of the brain. These processes are in turn responsible for the development of a vast repertoire of behaviors that characterizes the early years of life. In terms of motor development, both synaptic pruning and myelination are responsible for the improved precision and speed of coordinated movement. In addition, they are important in the development of cognitive skills. Improved perception of speech sounds and face recognition, for example, are likely the result of synaptic reorganization, a process that is dependent on experience.

Although development continues into early adult years, early childhood represents a period particularly important to development of a healthy brain. The foundations of sensory and perceptual systems that are critical to language, social behavior, and emotion are formed in the early years and are strongly influenced by experiences during this time. This is not to say that later development cannot affect these behaviors—on the contrary, experiences later in life are also very important to the function of the brain. However, experiences in the early years of childhood affect the development of brain architecture in a way that later experiences do not. In the following pages we will elaborate on how experience affects development between birth and 3 years of age.

Brain Beginnings: Constructing a Foundation for the Future

The development of the brain is a life-long process. Indeed, recent research suggests that the brain is capable of changing throughout the lifespan (Crawford , Pesch, & von Noorden, 1996; Jones, 2000; Keuroghlian & Knudsen, 2007), although perhaps not in all ways (e.g., humans do not “learn” to see or hear better as they age). However, the changes that take place during the early years are particularly important because they are the bedrock of what comes after. Higher level functions are dependent on lower level functions, the evidence for which is primarily in the basic cognitive processes and sensory perceptual systems. When infants are born, their brains are prepared for certain types of experience. For example, as discussed below, infants’ brains are tuned to the sounds of virtually all languages, but with experience, their brains become most tuned to their native language (see Kuhl, 2004, for discussion). This perceptual bias is the basis for learning language; the brain is partially tuned to be sensitive to language sounds but not so broadly tuned as to be sensitive to all possible sounds.

Subsequent language development builds on this initial sensitivity. Within the first year of life, infants learn to discriminate among sounds that are specific to the language they are exposed to in their particular environment. Before the time they are 6 months old, infants can discriminate among sounds of almost any language. Between 6 and 12 months, the brain begins to specialize in discriminating sounds of the native language and loses the ability to discriminate sounds in nonnative languages (Kuhl, Tsao, & Liu, 2003). This narrowing of perceptual sensitivity is important because it is related to later language ability in that better discrimination of native language sounds predicts better language skills later in life (Kuhl, 2004).

Sensitive Period: Plasticity Is Affected by Experience

The brain is much more sensitive to experience in the first few years of life than in later years. The plasticity of the brain underlies much of the learning that occurs during this period. In the language example in the previous section, we noted that infants are sensitive to most language sounds in the first half-year of life but during the second half they begin to specialize in their native tongue at the expense of the broad sensitivity to nonnative language sounds. The period of heightened sensitivity to language exposure is not, however, a critical period in the sense that infants can no longer learn the sounds of another language once it is over. In fact, 12-month-old infants given additional experience with speech sounds from a nonnative language continue to be able to discriminate among sounds (Kuhl, Tsao, & Liu, 2003).

Similarly, in the domain of *face processing*, an index of development of visual perception important to social behavior, 6-month-olds, 9-month-olds, and adults are all equally capable of discriminating between two human faces, whereas 6-month-olds alone can discriminate between two monkey faces (Pascalis, de Haan, & Nelson, 2002). However, 6-month-olds given 3 months of experience viewing a range of monkey faces retain the recognition ability at 9 months (Pascalis et al., 2005). Thus, the plasticity that characterizes brain processes during this time suggests that although the brain is particularly sensitive to experiences that occur, experience-dependent change is not limited to this short window. The sensitive period is effectively extended by specific experience.

A similar phenomenon exists in visual acuity, which is demonstrated by the natural occurrence of cataracts, rather than the laboratory manipulations discussed above. Maurer, Lewis, Brent, and Levin (1999) reported that for infants who are born with cataracts, a few moments of visual experience after the cataracts have been removed and replaced with new lenses leads to substantial improvements in visual acuity. This effect is stronger the sooner after birth this corrective procedure takes place. The longer the cataracts are left untreated, however, the lower the effect of experience on the outcome.

As demonstrated above, both speech and faces are initially processed by a broadly tuned window that then narrows with experience, yet the window can remain broader if experience includes a wide range of inputs. These studies suggest that the early period of life is characterized by sensitive periods that are dependent on the pattern of input from the environment. In response to certain input, the networks become biased, and future modifications become more difficult.

Deprivation: Environmental Effects on Brain Structure and Function

The effects of experience go beyond the simple modulation of plasticity. In fact, experience shapes the structure of the brain, a finding that has been demonstrated by the Bucharest Early Intervention Project (BEIP). This ongoing longitudinal study has found that institutionalization at a young age leads to severe consequences in the development of both brain and behavior. The study is following three groups of children: an Institutionalized group, children who have lived virtually all their lives in an institutional setting in Bucharest, Romania; a Foster Care group, which includes children who were institutionalized at birth and then placed in foster care (at a mean age of placement of 22 months); and a Never Institutionalized group, which includes children living with their biological families in the Bucharest region (for details see Zeanah et al., 2003). As discussed above, for healthy development of brain circuits, the individual needs to have healthy experiences; the lack of these may lead to the underspecification and miswiring of brain circuits. Children raised in institutional settings in Romania lack experiences that stimulate healthy growth and thus we would expect to see consequent “errors” in brain development giving rise to a range of problems. Indeed this is the case; the institutionalized children show patterns of physical and cognitive growth that are stunted and delayed, and they have very different patterns of brain activity when compared to children who have never been institutionalized (Marshall, Fox, & the BEIP Core Group, 2004). In addition, the effect of timing of experience is also important in preventing and amelioriating the effects of deprivation: children who were placed in foster care before they were 2 years old show patterns of brain activity that are more similar to never-institutionalized children than do those placed in foster care after they turn 2 (Marshall et al., 2008). The same general trends are also observed for IQ (Nelson et al., 2007) and language (Windsor et al., 2007). These results support the idea that the lack of good quality experience has detrimental effects on brain function and that once the child is older than 2 years these effects tend to be worse.

An important distinction that must be made here is between *deprivation* and *enrichment*. The studies described earlier took place in the context of deprivation, in comparison to a baseline norm in which certain needs of the child are met, not enrichment beyond the norm, and they clearly showed that a child deprived of a certain quality of experience will have abnormal brain development. These findings do not indicate, however, whether environments that provide more than the baseline norm will produce brain development that is in some way superior. So although the BEIP studies do suggest that a lack of good quality experience is detrimental, they do not provide evidence for the effects of enriched experience.

Conclusions

In this article we have attempted to illustrate how the developmental neurosciences can shed light on early childhood development. Prenatal development is largely driven by genetic processes, many of which are sensitive to the biochemical makeup of the mother's body but are under genetic regulation. In postnatal development, however, the environment plays a crucial role in fostering development, and the interactions between genetics and experiences account for most developmental outcomes. Brain research suggests that development is a hierarchical process of wiring the brain, in that higher level processes build on a foundation of lower level processes. For example, language development depends critically on sensory and perceptual development (e.g., discrimination of speech sounds). The types of stimuli infants and children are exposed to help shape the brain and behavior. Although the brain may come equipped with biases for certain perceptual information, such as for speech, language, or faces, it is the specific speech, language, and range of faces they are exposed to that drives subsequent development. Depriving young children of the kinds of experiences that are essential to later development—that is, the building blocks that create the scaffolding upon which development depends—leads to severe consequences in both brain structure and function. Studies of institutionalized children suggest that quality psychosocial experiences are necessary for the development of a healthy brain.

It is important to emphasize that the individual does not play a passive role in this process. By *experience* we do not mean events and circumstances that simply happen in an individual's life; rather, we define experience as the interaction between the individual and his or her environment. The individual is an agent that can shape his or her experience (Scarr & McCartney, 1983). For example, a child who appears happy in response to a caregiver singing a song may elicit more singing. This child consequently may have more experience with songs, which could affect his or her language development and the brain processes that underlie it.

Much of brain research is descriptive and simply tells us how the brain contributes to the development of behavior that is typical of young children (e.g., language and face processing). However, some of this research has implications on the decisions we make for young children. Research on deprivation can be used to make the case that environments that adversely affect infants and young children need to be remedied before they have long lasting consequences on both brain and behavior. Intervening in adverse circumstances is more successful if it occurs before brain processes become entrenched and in turn harder to rewire.

References

Aizawa H, Hu S-C, Bobb K, Balakrishnan K, Ince G, Gurevich I, Cowan M, Ghosh A. Dendrite development regulated by CREST, a Calcium-Regulated Transcriptional Activator. Science. 2004; 303:197–202. [PubMed: 14716005]

Crawford ML, Pesch TW, von Noorden GK. Excitatory binocular neurons are lost following prismatic binocular dissociation in infant monkeys. Behavioural Brain Research. 1996; 79:227–232. [PubMed: 8883834]

Huttenlocher PR, Dabholkar AS. Regional differences in synaptogenesis in human cerebral cortex. The Journal of Comparative Neurology. 1997; 387:167–178. [PubMed: 9336221]

Jones EG. Cortical and subcortical contributions to activity-dependent plasticity in primate somatosensory cortex. Annual Review of Neuroscience. 2000; 23:1–37.

Keuroghlian AS, Knudsen EI. Adaptive auditory plasticity in developing and adult animals. Progress in Neurobiology. 2007; 82:109–121. [PubMed: 17493738]

Kuhl PK. Early language acquisition: Cracking the speech code. Nature Reviews Neuroscience. 2004; 5:831–843.

Kuhl PK, Tsao FM, Liu HM. Foreign-language experience in infancy: Effects of short-term exposure and social interaction on phonetic learning. Proceedings of the National Academy of Sciences. 2003; 100:9096–9101.

Marshall P, Fox NA, the BEIP Core Group. A comparison of the electroencephalogram between institutionalized and community children in Romania. Journal of Cognitive Neuroscience. 2004; 16(8):1327–1338. [PubMed: 15532128]

Marshall P, Reeb BC, Fox NA, the BEIP Core Group. Effects of early intervention on EEG power and coherence in previously institutionalized children in Romania. Development and Psychopathology. 2008; 20:861–880. [PubMed: 18606035]

Maurer D, Lewis TL, Brent HP, Levin AV. Rapid improvement in the acuity of infants after visual input. Science. 1999; 286:108–110. [PubMed: 10506555]

Molliver M, Kostovic I, Van der Loos H. The development of synapses in the human fetus. Brain Research. 1973; 50:403–407. [PubMed: 4705508]

Nelson, CA.; de Haan, M.; Thomas, KM. Neural bases of cognitive development. In: Damon, W.; Lerner, R.; Kuhn, D.; Siegler, R., editors. Handbook of Child Psychology. Vol. Vol. 2. John Wiley & Sons; New Jersey: 2006. p. 3-57.

Nelson, CA.; Jeste, S. Neurobiological perspectives on developmental psychopathology. In: Rutter, M.; Bishop, D.; Pine, D.; Scott, S.; Stevenson, J.; Taylor, E., et al., editors. Textbook on Child and Adolescent Psychiatry. 5th ed. Blackwell Publishing; London: 2008. p. x-y.

Nelson CA, Zeanah CH, Fox NA, Marshall PJ, Smyke A, Guthrie D. Cognitive recovery in socially deprived young children: The Bucharest Early Intervention Project. Science. 2007; 318:1937–1940. [PubMed: 18096809]

Oppenheim, RW.; Johnson, JE. Programmed cell death and neurotrophic factors. In: Squire, LR.; Bloom, FE.; McConnell, SK.; Roberts, JL.; Spitzer, NC.; Zigmond, MJ., editors. Fundamental Neuroscience. 2nd ed. Academic Press; New York: 2003. p. 499-532.

Pascalis O, de Haan M, Nelson CA. Is face processing species-specific during the first year of life? Science. 2002; 296:1321–1323. [PubMed: 12016317]

Pascalis O, Scott LS, Kelly DJ, Dufour RW, Shannon RW, Nicholson E, Coleman M, Nelson CA. Plasticity of face processing in infancy. Proceedings of the National Academy of Sciences. 2005; 102:5297–5300.

Scarr S, McCartney K. How people make their own environments: A theory of genotype→environment effects. Child Development. 1983; 54(2):424–435. [PubMed: 6683622]

Windsor J, Glaze LE, Koga SF, the BEIP Core Group. Language acquisition with limited input: Romanian institution and foster care. Journal of Speech, Language, and Hearing Research. 2007; 50:1365–1381.

Zeanah CH, Nelson CA, Fox NA, Smyke AT, Marshall P, Parker SW, Koga S. Designing research to study the effects of institutionalization on brain and behavioral development: The Bucharest Early Intervention Project. Development and Psychopathology. 2003; 15:885–907. [PubMed: 14984131]