NATIONAL SCIENTIFIC COUNCIL ON THE DEVELOPING CHILD

The Timing and Quality of Early Experiences Combine to Shape Brain Architecture

WORKING PAPER 5

Center on the Developing Child HARVARD UNIVERSITY

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The Issue

THE FOUNDATIONS OF BRAIN ARCHITECTURE ARE ESTABLISHED EARLY IN LIFE THROUGH A CONTINUOUS series of dynamic interactions in which environmental conditions and personal experiences have a significant impact on how genetic predispositions are expressed.[1-7] Because specific experiences affect specific brain circuits during specific developmental stages—referred to as sensitive periods[8,9]—it is vitally important to take advantage of these early opportunities in the developmental building process. That is to say, the quality of a child's early environment and the availability of appropriate experiences at the right stages of development are crucial in determining the strength or weakness of the brain's architecture, which, in turn, determines how well he or she will be able to think and to regulate emotions.

Just as in the construction of a house, certain parts of the formative structure of the brain need to happen in a sequence and need to be adequate to support the long-term developmental blueprint. And just as a lack of the right materials can result in blueprints that change, the lack of appropriate experiences can lead to alterations in genetic plans. Moreover, although the brain retains the capacity to adapt and change throughout life, this capacity decreases with age.[10-12] Thus, building more advanced cognitive, social, and emotional skills on a weak initial foundation of brain architecture is far more difficult and less effective than getting things right from the beginning.[13]

The exceptionally strong influence of early experience on brain architecture makes the early years of life a period of both great opportunity and great vulnerability for brain development. An early, growth-promoting environment, with adequate nutrients, free of toxins, and filled with social interactions with an attentive caregiver, prepares the architecture of the developing brain to function optimally in a healthy environment.[14,15] Conversely, an adverse early environment, one that is inadequately supplied with nutrients, contains toxins, or is deprived of appropriate sensory, social, or emotional stimulation, results in faulty brain circuitry.[7,16-19] Once established, a weak foundation can have detrimental effects on further brain development, even if a healthy environment is restored at a later age.

The considerable susceptibility of the young, developing brain to the synergistic effects of environment and experience has enormous implications for policymakers, parents, and society. An abundance of scientific evidence clearly demonstrates that critical aspects of brain architecture begin to be shaped by experience before and soon after birth, and many fundamental aspects of that architecture are established well before a child enters school.[1,7-9,20-22]

> **Critical aspects of brain architecture begin to be shaped by experience before and soon after birth, and many fundamental aspects of that architecture are established well before a child enters school.**

Nevertheless, despite increasing public investment in K-12 education, there remains a persistent tolerance in our society for poor quality care and education in the early childhood period. In this context, scientific evidence indicates that for children to reach their full potential, communities need to support the capacity of all families to provide a variety of stimulating and appropriate experiences in the earliest years, when a child's brain is optimally programmed to benefit from specific types of experiences, and then build on that sturdy brain foundation through continuous exposures to high quality, age-appropriate experiences throughout the later school-age years.[23]

What Science Tells Us

The architecture of the brain depends on the mutual influences of genetics, environment, and experience. *Genetics* supplies a basic plan for brain development, just as an architect supplies a blueprint for building a house. The genetic plan instructs the basic properties of the nerve cells and lays down the basic rules for interconnecting nerve cells within and across circuits. In this manner, genes provide the initial construction plan for the brain's architecture.

The *environment* in which the brain begins to develop can have a profound influence on its initial architecture. Just as the selection of the best building materials enables the realization of the full potential of an architect's blueprint, a healthy environment beginning in the prenatal period allows the full potential of the genetic plan for the brain to be expressed. This includes an abundant supply of nutrients, an absence of toxins, and the healthy personal and social habits of the expectant mother.[14,15] Conversely, an environment lacking in critical nutrients, or containing toxins that result from unhealthy behaviors such as excessive maternal alcohol intake during pregnancy or lead ingestion in early childhood, can cause neurons to acquire abnormal properties and aberrant connections with other brain cells.[17,18,22] In addition, an adverse prenatal environment can actually alter the genetic plan for the brain.[19,32] These effects of threatening environmental conditions can cause neural circuits to change in ways that prevent them from functioning well, or at all, even in a subsequent healthy environment.

Experiences during sensitive periods of development play an exceptionally important role in shaping the capacities of the brain.

Experience refers to the interaction of a child with his or her environment. In humans, such experience begins before birth, as the fetus senses and responds to the environment of the womb.[18] This early experience influences the basic architecture of low-level circuits that mature at this early stage. After birth, experience plays an increasingly important role in shaping the architecture of developing neural circuits so that they function optimally for each individual.[8,15,20,33] Just as a master carpenter modifies the blueprint for a house to adapt to the needs of its setting and the people who will live in it, experience adjusts the genetic plan for the brain and shapes the architecture of its neural circuits according to the needs and distinctive environment of the individual.[2,6,15] Consequently, healthy and stimulating experience results in brain architecture that operates at its full genetic potential, and persistent adversity leads to weak brain architecture with impaired capabilities.

Early environments and experiences have an exceptionally strong influence on brain architecture. For most neural circuits, the effects that the environment and individual experience can exert on their architecture are particularly potent just as the circuit is maturing.[8] As a circuit begins to function, its chemical environment and the electrical information that it processes can have an enormous impact on that circuit, causing adjustments in its genetic plan and changing its architecture in fundamental ways. After most circuits have matured, their genetic plans and architecture can still be modified by experience, but the extent of these later modifications tends to be far more limited.

The period of exceptional sensitivity to the effects of environment and experience is called a *sensitive period* for that circuit. Because it is far more difficult to alter neural circuits substantially after their sensitive periods have ended, experiences during these sensitive periods play an exceptionally important role in shaping the capacities of the brain. Some examples of behavioral capacities that have been shown to be affected by sensitive periods of underlying circuitry include vision,[4,34] hearing,[10] language,[35] and responses to social cues.[2,13,15]

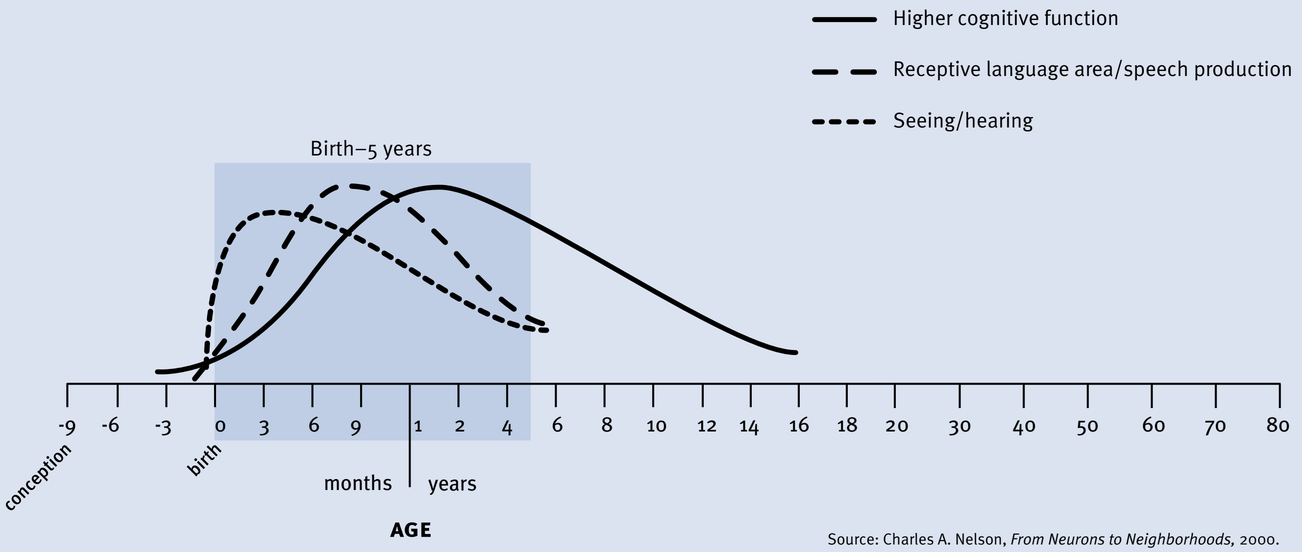
The increased flexibility of the circuitry in a young, developing brain is explained primarily by three factors. First, during its initial stages of formation, the brain develops far more extensive connections than it needs in order to function optimally, and connections that are not useful are pruned away over time.[4] Second, the molecular environment and cellular mechanisms that enable the formation of new connections and the elimination of incorrect connections are highly active in a circuit while it is maturing.[8] Finally, neural circuits are far more flexible before a particular pattern of connections has been shaped and fully activated.[1] Consequently, once a particular circuitry pattern becomes established, it is difficult for the effects of new and different experiences to alter that architecture.[36,37] This means that early experience has a unique advantage in shaping the architecture of developing brain circuits before they are fully mature and stabilized.

Different mental capacities mature at different stages in a child's development. Aspects of mental function are carried out by different hierarchies of neural circuits in the brain. The hierarchies of circuits that analyze visual information are different from those that process auditory information, learn language, remember recent events, plan future actions, or determine emotional responses. Because these various hierarchies mature at different times in a child's life,[24] the same environmental conditions will produce different cognitive and emotional experiences for a child, depending on his or her age.[20,25,26]

Even within a single hierarchy—such as visual, auditory, or language development—different neural circuits mature at different times. Circuits that process lower-level information mature earlier than those that process higher-level information.[27] For example, in the neural hierarchy that analyzes visual information, low-level circuits that analyze color, shape, or motion are fully mature long before the higher-level circuits that interpret complex stimuli, such as facial expressions, or identify meaningful inputs such as frequently used objects.[26,28-30] For the developing brain, this means that the ability to perceive simple aspects of the world and to make simple emotional and social judgments develops long before the ability to make sophisticated, cognitive analyses.[20,31] Stated simply, children's ability to interpret what they see changes over time as their brain circuitry is built. Thus, it is important that experiences provided in the earliest years are appropriate for the young child's stage of development. Reading a picture book with a toddler who is learning to speak, for example, provides an important opportunity to point to and talk about the pictures, not to focus on the written words. The ability to decode written language comes later, when the appropriate, higher-level brain circuitry will be built.

Sensitive periods occur at different ages for different parts of the brain. Different neural circuits pass through sensitive periods at different ages. The sensitive periods for neural circuits that perform low-level analyses of sensory stimuli tend to end before or soon after birth.[38,39] In contrast, the sensitive periods for high-level circuits that process sophisticated aspects of the world, such as communication signals (including language)

Synapse Formation in the Developing Brain



Source: Charles A. Nelson, *From Neurons to Neighborhoods,* 2000.

or the interpretation of facial expressions, end much later in development.[26,35,40]

Because low-level circuits mature early and high-level circuits mature later, different kinds of experiences are critical at different ages for optimal brain development,[41] a concept called *age-appropriate experience*. Soon after birth, basic sensory, social, and emotional experiences are essential for optimizing the architecture of low-level circuits. At later ages, more sophisticated kinds of experiences are critical for shaping higher-level circuits. When adults or communities expect young children to master skills for which the necessary brain circuits have not yet been formed, they waste time and resources, and may even impair healthy brain development by inducing excessive stress in the child.

Stimulating early experiences lay the foundation for later learning. High-level neural circuits that carry out sophisticated mental functions depend on the quality of the information that is provided to them by lower-level circuits. Low-level circuits whose architecture was shaped by healthy experiences early in life provide high-level circuits with precise, high-quality information. High-quality information, combined with sophisticated experiences later in life, allows the architecture of circuits involved in higher functions to take full advantage of their genetic potential. Thus, early learning lays the foundation for later learning and is essential (though not sufficient) for the development of optimized brain architecture. Stated simply, stimulating early experience must be followed by more sophisticated and diverse experiences later in life, when high-level circuits are maturing, in order for full potential to be achieved.[13,20,42,43]

Impoverished early experience can have severe and long-lasting detrimental effects on later brain capabilities. Sensitive periods act as double-edged swords. On the one hand, a sensitive period enables a neural circuit to optimize its architecture for the needs and environment of the individual.[33,44] On the other hand, this period of extreme receptivity also makes the circuit vulnerable to the damaging effects of adversity.[16,45] Just as a faulty foundation has far-reaching detrimental effects on the strength and quality of a house, adverse early experience can have far-reaching detrimental effects on the development of brain architecture.

Stressful experiences during sensitive periods alter the function and architecture of specific neural circuits, as these circuits adapt their functional properties to the adversity that has been experienced.[8,10,38] As shown by experiments in which animals have been subjected to significant stress, when the adverse conditions last through the end of a circuit's sensitive period, the changes in the circuit's architecture become stable and tend to persist in the adult brain.[46,47] Subsequently, although the brain's residual capacity for plasticity can mitigate the adverse effects of the altered circuit architecture,[10] the affected neural circuits do not process information as well as they could have if the animal had been exposed to an appropriate experience during the sensitive period. The degraded information that is transmitted by the altered neural circuit can prevent high-level circuits from receiving the information they need to shape their architectures optimally, even after a rich environment has been restored later in life.

Brain plasticity continues throughout life. Neural circuits, particularly those that are specialized for learning, continue to adapt their architecture in response to experience throughout the adult years.[10,11] Even circuits that pass through sensitive periods maintain a degree of flexibility that allows them to adapt their architecture, at least partially, to experience in adulthood.[12,48] The plasticity of many of these circuits in adult animals can be enhanced significantly by intentionally drawing attention to the information that is being processed by the circuit.[10] For example, plasticity in the representation of sound frequencies in the auditory cortex can be induced in adults—long after the appropriate sensitive period has ended—by having adult animals attend to particular sound frequencies to receive a food reward.[49] The residual capacity for plasticity in mature neural circuits thus allows for some recovery of brain capabilities, even in adults. In order for the brain to take full advantage of this plasticity, experience needs to be tailored to activate the relevant neural circuits and the individual's attention must be engaged in the task.[7] The implications for later interventions in development are clear—the task will be harder, more expensive in terms of societal and individual effort, and potentially less extensive and durable.

Popular Misrepresentations of Science

AS ADVANCES IN NEUROSCIENCE HAVE RECEIVED increasing attention, there has been parallel growth in the appetite for information about how to use scientific knowledge to enhance early brain development. This creates both important opportunities for more informed investments in young children, and the danger of unrealistic or misleading applications, sometimes with altruistic intentions and at other times simply for commercial profit. Within this context, it is essential that we differentiate scientific fact from common misperceptions.

Although a great deal of brain architecture is shaped during the first three years, claims that the window of opportunity for brain development closes on a child's third birthday are completely unfounded. Basic aspects of brain function, such as our ability to see and hear effectively, do depend critically on very early experiences. Some aspects of emotional development also conform to this concept. Nevertheless, vast regions of the brain that are responsible for higher order functions—including most cognitive, social, and emotional capacities—have not yet begun to mature by age three or are at extremely early stages of maturation. Thus, although the basic principle of early plasticity generally applies (i.e., "earlier is better than later"), the important time periods for experience depend on the specific function of interest. For most functions, the window of opportunity remains open well beyond age three.

Studies of the adverse effects of deprivation on brain development tell us little about the benefits of enrichment. Much of what we know about the impact of early experience on brain architecture comes from animal or human studies of deprivation. Examples include the negative effect on the development of vision from a cataract present at birth or an untreated strabismus (i.e., "lazy eye") early in life; adverse impacts on language and behavior as a result of delayed detection and intervention for a congenital hearing impairment; and the devastating effects on all aspects of development when a child is brought up in a bleak and neglectful orphanage. It is important to emphasize, however, that well-documented, scientific evidence of the negative impacts of deprivation on brain circuitry does not necessarily mean that excessive enrichment produces measurable enhancements in brain architecture.

There are no credible scientific data to support the claim that specialized videos or particular music recordings (e.g., "the Mozart Effect") have a positive, measurable impact on developing brain architecture. Beyond recent research that has argued against such claims,[50] evidence from decades of scientific investigation of experience-induced changes in brain development makes it highly unlikely that the potential benefits of such media would even come close to matching (much less exceeding) the more important influences of attentive, nurturing, and growth-promoting interactions with invested adults. Although a varied array of experiences clearly stimulates learning in the preschool years, promotional statements about the superior brain-building impacts of expensive "educational" toys and videos for infants and toddlers have no scientific support.[51,52] Similarly, didactic instruction in skill areas that are developmentally inappropriate for young children (i.e., the underlying neural circuitry necessary to master the particular skill has not developed) is an exercise in futility. Attempting to teach one-year olds to read is an example of such misguided efforts. The issue is not whether the child is "smart enough" or "motivated" to learn, but whether the necessary brain circuitry is sufficiently "wired" to support the specific domains required for that learning.

> **Well-documented, scientific evidence of the negative impacts of deprivation on brain circuitry does not mean that excessive enrichment produces measureable enhancements in brain architecture.**

The Science-Policy Gap

Practical experience tells us that it is easier to teach a "slow" first grader how to read than it is to train an illiterate adult for a job that pays a living wage. We don't need sophisticated research to prove that aggressive preschoolers are easier to "rehabilitate" than violent criminals. Common sense tells us that the learning and behavior problems of young children can be fixed more easily and at less cost than those of adolescents and young adults. Neuroscience tells us why these statements are all true.

Scientific evidence about how brains develop makes it very clear that neural circuits are shaped by time-specific experiences, and that the impact of a given experience is influenced by the nature of the circuits that are being formed at that time.

> **The convergence of neuroscience and economics tells us that the clock is always ticking, and the costs of ignoring problems keep rising.**

Moreover, the convergence of neuroscience and economics tells us that the clock is always ticking, and the costs of ignoring problems keep rising as time passes. Notwithstanding these fundamental principles of biology and human capital formation, the critical importance of time is often ignored in the world of early childhood policy. This striking gap between science and policy is illustrated by the following examples.

The child welfare system is typically characterized by cumbersome and protracted decision-making processes that leave young children vulnerable to the adverse impacts of significant stress during sensitive periods of early brain development. The powerful and far-reaching effects of severely adverse environments and experiences on brain development make it crystal clear that time is not on the side of an abused or neglected child whose physical and emotional custody remains unresolved in a slow-moving bureaucratic process. The basic principles of neuroscience indicate the need for a far greater sense of urgency regarding the prompt resolution of such decisions as when to remove a child from the home, when and where to place a child in foster care, when to terminate parental rights, and when to move towards a permanent placement. The window of opportunity for remediation in a child's developing brain architecture is time-sensitive and time-limited.

Education reform efforts that invest significant resources in the training, recruitment, and retention of skilled teachers for K-12 will have greater impact if they also include higher standards and more rigorous professional credentials for preschool programs. Research shows that staff knowledge and skills are among the most important determinants of the impact of early childhood programs.[53,54] Consequently, when model programs that have been proven to be effective are "taken to scale" with less well-compensated personnel who have less expertise, it is not surprising that comparable benefits are often not realized.[23] Stated simply, effective preschool investments require well-trained staff whose knowledge and skills match the needs of the children and families they are asked to serve. Poorly qualified personnel (whose low salaries provide immediate cost savings) compromise the effectiveness of preschool education programs and diminish the ultimate returns that can be achieved from subsequent K-12 investments.

Education policies disregard fundamental concepts of neuroscience when they delay teaching second languages until early adolescence and simultaneously undervalue bilingual programs for young children. Beginning at birth, all children have the capacity to learn any of the world's languages. This ability is encoded in our genes and activated by exposure to everyday conversation in an interactive way. Unless a child has a specific disability, the achievement of fluency in any language, as well as the mastery of more than one language at the same time, does not require formal instruction or intervention in the early childhood years. It simply requires ongoing communication with others. Moreover, the younger the brain, the greater its capacity to master more than a single langauge. If education policies were guided by what we know about the development of the brain, second-language learning would be a preschool priority.

Implications for Policy and Programs

THE SCIENCE OF EARLY BRAIN DEVELOPMENT is sufficiently mature to support a number of evidence-based implications for those who develop and implement policies that affect the health and well-being of young children. Central to this conclusion are the core concepts of sensitive periods and neuroplasticity, which convey three important messages. First, both brain development and behavior are shaped by experience over time. Second, both the architecture of the brain and established patterns of behavior are increasingly difficult to change as individuals get older. Third, it is more effective and more efficient to get things right the first time than to try to fix them later.

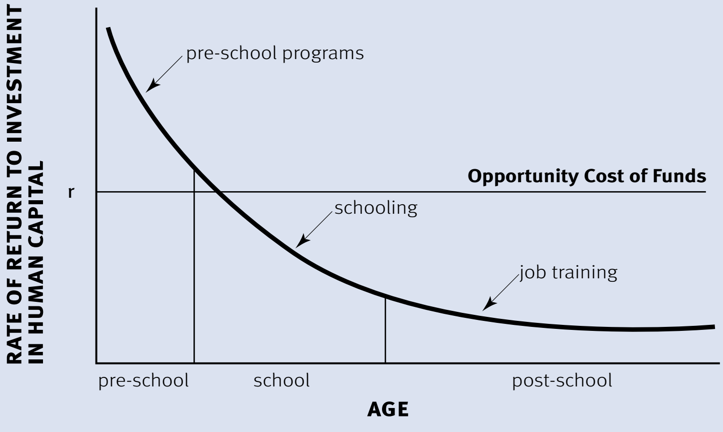
There is considerable evidence that public policies can have a significant impact on promoting the healthy development of young children, above and beyond the central importance of family influences. This is particularly compelling for children who experience significant adversity during the early childood years. The following four points are particularly worthy of thoughtful consideration.

The basic principles of neuroscience and the econometrics of human capital development both suggest that early and effective intervention for the most vulnerable children will generate the greatest financial payback. In recent years, a growing body of sophisticated economic analyses has contributed an important new dimension to the public debate about the value to society of investing in the care and education of young children who are at risk for later failure in school and in the workplace. Extensive data now indicate that policymakers can achieve greater return on investments in early education for children from families with low income and limited parent education than they can from investments in remedial programs for adults with limited workforce skills.[13,55] In short, although optimal financial benefits depend on continued investment throughout the middle childhood years, the greatest returns are realized when investments are made in the lives of vulnerable children well before they begin school.

Increasing the availability of *evidence-based*, two-generation programs that begin immediately after birth (and preferably prenatally), can enhance the experiences of young children in families with limited education and low income. The environment of relationships in which young children live literally shapes the architecture of their brains. Effective programs provide center-based, growth-promoting experiences for the children, as well as help their parents create a home environment that provides the kind of positive social interactions, rich language exposure, and early literacy experiences that increase the probability that their child will enter school with the social, emotional, and cognitive skills needed to succeed. These supportive interventions can be made available through voluntary associations, community-based organizations, and employer-sponsored initiatives, as well as through government-funded services. Because not all such services are effective, it is essential that funds be invested in programs that have been shown to have measurable impacts.[23]

Enrolling all children who meet the eligibility criteria for early intervention programs as early as possible would help infants and toddlers with developmental delays and disabilities build the foundational skills needed to realize their full potential. When compensatory adjustments are facilitated as early as possible, they help build a

Return on Investment Over Time



Rates of return to investment in human capital as function of age when the investment was initiated. The data were derived from a life cycle model of dynamic human capital accumulation with multiple periods and credit constraints. Investments were initially set to be equal across all ages. 'r' represents the cost of the funds. Data are from Cunha et al (2005).
Source: Knudsen, et al.[13]

sturdier foundation for the later achievement of higher-level skills. This underscores the urgent need to identify sensory impairments as soon after birth as possible, so that corrective devices (e.g., hearing aids and eyeglasses) as well as appropriate habilitative services can be provided during the time that basic neural circuits are being established. Outcomes for children with cognitive impairments are also improved significantly by the facilitation of early learning experiences that build a stronger foundation upon which increasingly higher-level brain circuits and more complex skills can be built over time.

Providing developmental assessments and intervention services for young children experiencing significant adversity *before* they exhibit problems in their behavior or development will increase their chances for more positive life outcomes. Strong and persistent activation of the body's stress response systems (i.e., increases in heart rate, blood pressure, and stress hormones such as cortisol and cytokines) can result in the permanent disruption of brain circuits during the sensitive periods in which they are maturing. Common causes of such "toxic" stress include child abuse, serious neglect, and prolonged or repeated exposure to violence, which may be associated with deep poverty, parental substance abuse, or maternal mental illness, such as severe depression. The provision of both prevention and early intervention services for the large number of young children and families currently engaged in the nation's child welfare systems offers a compelling and promising place to start. Although this would require significant increases in short-term funding, effective programs for such highly vulnerable, young children are likely to generate a substantial return on investment through significant reductions in the later costs of special education, grade retention, welfare assistance, and incarceration.[23]

References

1. Hensch, T.K. (2005). Critical period mechanisms in developing visual cortex. *Current Topics in Developmental Biology*, 69, 215-237.
2. Horn, G. (2004). Pathways of the past: the imprint of memory. *Nature Reviews Neuroscience*, 5, 108-120.
3. Friederici, A.D. (2006). The neural basis of language development and its impairment. *Neuron*, 52, 941-952.
4. Katz, L.C. & Shatz, C.J. (1996). Synaptic activity and the construction of cortical circuits. *Science*, 274, 1133-1138.
5. Singer, W. (1995). Development and plasticity of cortical processing architectures. *Science*, 270, 758-764.
6. Majdan, M. & Shatz, C.J. (2006). Effects of visual experience on activity-dependent gene regulation in cortex. *Nature Neuroscience*, 9, 650-659.
7. Grossman, A.W., Churchill, J.D., McKinney, B.C., Kodish, I.M, Otte, S.L., & Greenough, W.T. (2003). Experience effects on brain development: possible contributions to psychopathology. *Journal of Child Psychology and Psychiatry*, 44, 33-63.
8. Knudsen, E.I. (2004). Sensitive periods in the development of the brain and behavior. *Journal of Cognitive Neuroscience*, 16, 1412-1425.
9. Hess, E.H. (1973). *Imprinting: Early experience and the developmental psychobiology of attachment.* New York: Van Nostrand Reinhold Company.
10. Keuroghlian, A.S. & Knudsen, E.I. (2007). Adaptive auditory plasticity in developing and adult animals. *Progress in Neurobiology*, 82, 109-121.
11. Buonomano, D.V. & Merzenich, M.M. (1998). Cortical Plasticity: From Synapses to Maps. *Annual Review of Neuroscience*, 21, 149-186.
12. Karmarkar, U.R. & Dan, Y. (2006). Experience-dependent plasticity in adult visual cortex. *Neuron*, 52, 577-585.
13. Knudsen, E.I., Heckman, J.J., Cameron, J.L., & Shonkoff, J.P. (2006). Economic, neurobiological, and behavioral perspectives on building America's future workforce. *Proceedings of the National Academy of Sciences U S A, 103*, 10155-10162.
14. Tang, A.C., Akers, K.G., Reeb, B.C., Romeo, R.D., & McEwen, B.S. (2006). Programming social, cognitive, and neuroendocrine development by early exposure to novelty. *Proceedings of the National Academy of Sciences U S A, 103*, 15716-15721.
15. Weaver, I.C., Cervoni N., Champagne F.A., D'Alessio, A.C., Sharma, S., Seckl, J.R., et al. (2004). Epigenetic programming by maternal behavior. *Nature Neuroscience*, 7, 847-854.
16. Rice, D. & Barone, S., Jr. (2000). Critical periods of vulnerability for the developing nervous system: evidence from humans and animal models. *Environmental Health Perspectives*, 108(Suppl 3), 511-533.
17. Levitt, P. (2003). Structural and functional maturation of the developing primate brain. *Journal of Pediatrics*, 143, S35-45.
18. Center on the Developing Child at Harvard University. (2006). *Early exposure to toxic substances damages brain architecture*, Working Paper No. 4. http://www.developingchild.net/pubs/wp/Early_Exposure_Toxic_Substances_Brain_Architecture.pdf.
19. Sabatini, M.J., Ebert P., Lewis, D.A., Levitt, P., Cameron, J.L, Mirnics, K. (2007). Amygdala gene expression correlates of social behavior in monkeys experiencing maternal separation. *Journal of Neuroscience*, 27, 3295-3304.
20. Kuhl, P.K. (2004). Early language acquisition: cracking the speech code. *Nature Reviews Neuroscience*, 5, 831-843.

21. Matsuzawa, T., Tomonaga, M., & Tanaka, M. (eds.). (2006). *Cognitive Development in Chimpanzees.* Tokyo: Springer.
22. Center on the Developing Child at Harvard University. (2005). *Excessive stress disrupts the architecture of the developing brain*, Working Paper No. 3. http://www.developingchild.net/pubs/wp/Stress_Disrupts_Architecture_Developing_Brain.pdf.
23. National Scientific Council on the Developing Child. (2007). *A science-based framework for early childhood policy: Using evidence to improve outcomes in learning, behavior and health for vulnerable children.* http://www.developingchild.net/pubs/persp/pdf/Policy_Framework.pdf.
24. Gogtay, N., Giedd, J.N., Lusk, L., Hayashi, K.M., Greenstein, D., Vaituzis, A.C., et al. (2004). Dynamic mapping of human cortical development during childhood through early adulthood. *Proceedings of the National Academy of Sciences U S A*, 101, 8174-8179.
25. Yurgelun-Todd, D. (2007). Emotional and cognitive changes during adolescence. *Current Opinion in Neurobiology*, 17, 251-257.
26. Pascalis, O., de Haan, M., & Nelson, C.A. (2002). Is face processing species-specific during the first year of life? *Science*, 296, 1321-1323.
27. Burkhalter, A., Bernardo, K.L., & Charles, V. (1993). Development of local circuits in human visual cortex. *Journal of Neuroscience*, 13, 1916-1931.
28. Scherf, K.S., Behrmann, M., Humphreys, K., & Luna, B. (2007).Visual category-selectivity for faces, places and objects emerges along different developmental trajectories. *Developmental Science*, 10, F15-30.
29. Golarai, G., Ghahremani, D.G, Whitfield-Gabrieli, S., Reiss, A., Eberhardt, J.L., Gabrieli, J.D, et al. (2007). Differential development of high-level visual cortex correlates with category-specific recognition memory. *Nature Neuroscience,* 10, 512-522.
30. Pascalis, O., Scott, L.S., Kelly, D.J., Shannon, R.W., Nicholson, E, Coleman, M., et al. (2005). Plasticity of face processing in infancy. *Proceedings of the National Academy of Sciences U S A*, 102, 5297-5300.
31. Thompson, R.A. (2001). Development in the first years of life. *The future of children*, 11, 20-33.
32. Weaver, I.C., Champagne, F.A., Brown, S.E., Dymov, S., Sharma, S., Meany, M.J., et al. (2005). Reversal of maternal programming of stress responses in adult offspring through methyl supplementation: altering epigenetic marking later in life. *Journal of Neuroscience, 25*, 11045-11054.
33. DeBello, W.M., Feldman, D.E., & Knudsen, E.I. (2001). Adaptive axonal remodeling in the midbrain auditory space map. *Journal of Neuroscience, 21*, 3161-3174.
34. Hubel, D.H. & Wiesel, T.N. (1977). Ferrier Lecture: Functional architecture of macaque monkey visual cortex. *Proceedings of the National Academy of Sciences*, 198, 1-59.
35. Newport, E.L., Bavelier, D., & Neville, H.J. (2001). Critical thinking about critical periods: Perspectives on a critical period for language acquisition. In E. Doupoux (Ed.), *Language, brain and cognitive development: Essays in honor of Jacques Mehler* (pp 481-502). Cambridge, MA: MIT Press.
36. Feldman, D.E. (2000). Inhibition and plasticity. *Nature Neuroscience*, 3, 303-304.
37. Zheng, W. & Knudsen, E.I. (2001). GABAergic inhibition antagonizes adaptive adjustment of the owl's auditory space map during the initial phase of plasticity. *Journal of Neuroscience*, 21, 4356-4365.
38. Daw, N.W. (1997). Critical periods and strabismus: what questions remain? *Optometry and Vision Science*, 74, 690-694.
39. Jones, E.G. (2000). Cortical and subcortical contributions to activity-dependent plasticity in primate somatosensory cortex. *Annual Review of Neuroscience*, 23, 1-37.
40. Doupe, A.J. & Kuhl, P.K. (1999). Birdsong and Human Speech: Common Themes and Mechanisms. *Annual Review of Neuroscience.* 22, 567-631.
41. Black, J.E. & Greenough, W.T. (1986). Induction of pattern in neural structure by experience: Implications for cognitive development. In M.E. Lamb, A.L. Brown, & B. Rogoff (Eds.), *Advances in developmental psychology*, Volume 4 (pp 1-50). Hillsdale, NJ:.Lawrence Erlbaum Associates.
42. DeBello, W.M. & Knudsen, E.I. (2004). Multiple sites of adaptive plasticity in the owl's auditory localization pathway. *Journal of Neuroscience*, 24, 6853-6861.
43. Nelson, C.A., de Haan, M., & Thomas, K.M. (2006). Neural bases of cognitive development. In W. Damon, R. Lerner, D. Kuhn, & R. Siegler (Eds.), *Handbook of Child Psychology*, Volume 2. New Jersey: John Wiley & Sons, Inc..
44. Antonini, A. & Stryker, M.P. (1993). Rapid remodeling of axonal arbors in the visual cortex. *Science*, 260, 1819-1821.
45. Nelson, C.A. (2007). A neurobiological perspective on early human deprivation. *Child Development Perspectives*, 1, 13-18.
46. Linkenhoker, B.A., von der Ohe, C.G., & Knudsen, E.I. (2005). Anatomical traces of juvenile learning in the auditory system of adult barn owls. *Nature Neuroscience*, 8, 93-98.
47. Antonini, A., Fagiolini, M., & Stryker, M.P. (1999). Anatomical correlates of functional plasticity in mouse visual cortex. *Journal of Neuroscience*, 19, 4388-4406.
48. Bergan, J.F., Ro, P., Ro, D., & Knudsen, E.I. (2005). Hunting increases adaptive auditory map plasticity in adult barn owls. *Journal of Neuroscience*, 25, 9816-9820.
49. Polley, D.B., Steinberg, E.E., & Merzenich, M.M. (2006). Perceptual learning directs auditory cortical map reorganization through top-down influences. *Journal of Neuroscience*, 26, 4970-4982.
50. Jones, S.M. & Zigler, E. (2002). The Mozart effect: Not learning from history. *Applied Developmental Psychology*, 23, 355-372.
51. Zimmerman, F.J., Christakis, D.A., & Meltzoff, A.N. (2007). Television and DVD/video viewing in children younger than 2 years. *Archives of Pediatrics & Adolescent Medicine*, 161, 473-479.
52. Zimmerman, F.J., Christakis, D.A., & Meltzoff, A.N. (2007). Associations between media viewing and language development in children under age 2 years. *Journal of Pediatrics*, 151, 364-368.
53. Gormley, W.T., Jr., Gayer, T., Phillips, D., & Dawson, B. (2005). The effects of universal pre-K on cognitive development. *Developmental Psychology*, 41, 872-884.
54. Early, D.M., Maxwell, K.L., Burchinal, M., Alva, S., Bender, R.H., Bryant, D., et al. (2007). Teachers' education, classroom quality, and young children's academic skills: results from seven studies of preschool programs. *Child Development*, 78, 558-580.
55. Cunha, F., Heckman, J., Lochner, L., & Masterov, D. (2005). *Interpreting the evidence on life skill formation*, Working Paper #10091. Cambridge, MA: National Bureau of Economic Research.

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