• Please reference (top of page) the words All or bracket items for background ALL information.

Neural Connections: Some You Use, Some You Lose

By John Bruer

Over 20 years ago, neuroscientists discovered that humans and other animals experience a rapid increase in brain connectivity - an exuberant burst of synapse formation - early in development. They have studied this process most carefully in the brain's outer layer, or cortex, which is essentially our gray matter. In these studies, neuroscientists have documented that over our life spans the number of synapses per unit area or unit volume of cortical tissue changes, as does the number of synapses per neuron. Neuroscientists refer to the number of synapses per unit of cortical tissue as the brain's synaptic density. Over our lifetimes, our brain's synaptic density changes in an interesting, patterned way. This pattern of synaptic change and what it might mean is the first neurobiological strand of the Myth of the First Three Years. (The second strand of the Myth deals with the notion of critical periods, and the third takes up the matter of "enriched," or complex, environments.)

Popular discussions of the new brain science trade heavily on what happens to synapses during infancy and childhood. Magazine articles often begin with colorful metaphors suggesting that what parents do with their infant has a powerful, lifelong impact on their baby's brain that determines the child's adult intelligence, temperament, and personality.

A *Newsweek* Special Edition tells us, "Every lullaby, every giggle and peek-a-boo, triggers a crackling along his neural pathways, laying the groundwork for what could someday be a love of art or a talent for soccer or a gift for making and keeping friends."1 Also according to *Newsweek*, "You hold your newborn so his sky blue eyes are just inches from the brightly patterned wallpaper. Zzzt: a neuron from his retina makes an electrical connection with one in his brain's visual cortex. You gently touch his hand with a clothespin: he grasps it, drops it, and you return it to him with soft words and a smile. *Crackle*: neurons from his hand strengthen their connection to those in his sensory-motor cortex."2

Notice that these metaphors associate the neural crackling and zapping with rather mundane, commonplace activities giggling, peek-a-boo, playing with clothespins. This is appropriate. Brain science has not pointed to new ways of raising or teaching children that will *really* stimulate those synapses above and beyond what normal experiences provide. Thus the metaphors do properly convey that brain-based parenting amounts to doing no more than what most parents do normally.

In popular articles, the crackling and zapping metaphors are often followed by similes that provide accessible, colorful analogies of what goes on early in brain development. They tell us that, although some of the neurons in the newborn's brain are genetically hardwired at birth to control vital functions, like breathing and controlling body temperature, trillions and trillions of others "are just waiting to be hooked up and played like orchestra instruments in a complex musical composition. Parents, educators, the babies' early experiences - all these factors will determine which neurons connect and which connections will eventually wither and die from lack of use."3 Or to use a more technological image, infants' neurons "are like the Pentium chips in a computer before the factory pre-loads the software. They are pure and of almost infinite potential, unprogrammed circuits that might one day compose rap songs and do calculus, erupt in fury and melt in ecstasy .... It is the experiences of childhood, determined by which neurons are used, that wire the brain as surely as a programmer at a keyboard reconfigures the circuits in a computer. Which keys are typed which experiences a child has - determines whether the child grows up to be intelligent or dull, fearful or self-assured, articulate or tongue-tied."4

These metaphors and similes convey the image of infinitely modifiable infant brains. Neurons are in place awaiting the appropriate experiences and stimulation that will build synaptic connections among them. This figurative language - and the picture it paints -captures the popular understanding of early brain development and the understanding conveyed in the literature of the Myth of the First Three Years. We are left with the idea that infant brains are exuberantly growing and connecting in direct response to the actions of watchful singing, reading, and talking parents and caregivers.

ALL

But does this idea accurately capture what neuroscientists know about synapse formation early in brain development- How well does the neuroscientific evidence that the Mythmakers cite support this popular understanding-

Neurons, Synapses, and Brain Development

What happens to synapses during development, and why, are fundamental questions for modern neuroscience. As one prominent textbook, Eric Kandel and James Schwartz's *Principles of Neural Science*, says, "Behavior depends on the formation of appropriate interconnections among neurons in the brain."5 Or as Patricia Goldman-Rakic, another neuroscientist who has conducted extensive research on primate brain development, puts it, "The synaptic architecture of the cerebral cortex defines the limits of intellectual capacity, and the formation of appropriate synapses is the ultimate step in establishing these functional limits."6

Neuroscientists do know that rapid synapse formation occurs early in the development of complex nervous systems, like those of cats, primates, and humans. Before we proceed to look at what neuroscience has learned about early, rapid synapse formation, we should first have a better idea of what developmental events precede it.

Neurons come in a variety of shapes and forms, but they all have a cell body that contains the cell nucleus. Most neurons have branches extending from the cell body. Axons, the long branches in the cells (usually enclosed in a myelin sheath), carry nerve impulses away from the cell body to other neurons. Dendrites, the shorter branches, generally receive nerve impulses from the axons of other neurons and transmit those impulses toward the cell body.

Usually, nerve cells are not in direct physical contact. There are microscopic gaps between the axons of one neuron and the dendrites of its neighbors. Communication between neurons takes place across these microscopic gaps or synapses. Chemical neurotransmitters move across the gaps from the presynaptic ending of the axon to the postsynaptic membrane of the adjoining dendrite. These chemical messengers then either excite or inhibit electrical activity in the postsynaptic cell. Via their synaptic connections, brain cells form the neural circuits that somehow support our sensory, motor, and cognitive skills and that ultimately regulate all of our behavior.

Neurons do not begin life in a mature state. They take time to develop. Neurons begin to form very early in fetal development. All our neurons derive from a single, thin layer of tissue in an embryonic structure called the neural tube. In humans, the first neurons that will eventually become part of the brain's cortical "gray matter" begin to appear at around 42 days after conception. During the next 120 days, around 120 days before birth, the full complement of our cortical neurons forms. The received neuroscientific view has been that we humans, along with our primate cousins, acquire all the cortical neurons we will ever have during roughly the middle third of gestation. (This view has been assumed in all the brain and early childhood literature, but recent research reported in October 1999 by Charles Gross and Elizabeth Gould is causing scientists to reconsider this assumption. Gross and Gould found that, in monkeys, newly formed neurons appear in the brain cortex continuously throughout the monkeys' lives.) When one considers that the human brain at birth contains on the order of 100 billion neurons, this means that during those 120 days, neurons form at a rate of around 580,000 per minute.

As cortical neurons form and the fetal brain grows, the neurons migrate from where they are first formed to their final position in the cortex. During this migration, neurons begin to grow axons and dendrites, the structures that will eventually allow them to form synapses and to build neural circuits.

The process by which axons reach their dendritic targets is not an arbitrary, random one. The brain has to form the correct contacts and circuits between axons and dendrites. Sometimes, the axons must traverse relatively vast distances - on an axonal scale, distances equivalent to our making a coast-to-coast U.S. trip - to find their appropriate target cells. Genetic mechanisms guide this neural mass migration. Following a trail blazed by physical, mechanical, and chemical markers, axons reach and identify their appropriate target cells. They even find the appropriate sites on the target cells' dendrites. In humans, the migration begins about four months before birth and ends shortly after birth. Once the axons and target cells recognize each other, synapses begin to form almost immediately.

In humans, synapse formation starts at around two months before birth and continues at least through the first year of life. The popular and policy interest in brain development begins at this point. It begins with considering what happens to synapses following birth, during infants' first three years of life.

Synaptic Density: Counting Needles in the Neurological Haystack

Neuroscientists discovered the period of rapid, postnatal synapse formation nearly 25 years ago. In these studies, scientists take samples of brain tissue from the same brain area of animals or humans that differ in age. In animal studies, the animals are sacrificed at different ages to obtain the tissue samples. In human studies, scientists must rely on samples of brain tissue taken at autopsy. This makes

human studies a bit more difficult, because scientists are limited in the number of brains they can study and have little control over how many brains at each developmental age they can include in a study. In the animal and human samples, the scientists then count synapses, or structures associated with synapses, to see how synaptic densities -the number of synapses per unit area or unit volume of cortical tissue vary over the life span in a species.

Counting synapses in studies like these is the scientific equivalent of estimating the number of needles in a haystack, when both the number of needles and the size of the haystack are changing at constantly differing rates. This is not work for the timid, impulsive, or impatient. For a series of studies on rhesus monkeys done during the 1980s, Pasko Rakic and his colleagues at Yale University first used electron micrographs to enlarge the tissue specimens 14,000 times. They then counted the synapses in each of at least four specimens from dozens of animals. They counted over 500,000 synapses in 25,000 electron micrographs. From these counts, they calculated average synaptic densities.7

Calculating reliable densities also presents a series of needle-in-the-haystack methodological problems. Brains grow and undergo age-related changes, with different kinds of brain tissue growing at different rates - neurons, nonneuronal brain cells, the space around cells, myelin sheaths on axons, and the number and size of blood vessels. Synapse counters must take account of and adjust for all these factors. They have to make reasoned assumptions to compensate for possible sampling errors, because there is no way they can count all the synapses in even one brain area. Scientists differ in how they choose to address these problems. These technological and methodological differences can complicate direct comparisons across studies and certainly across species.

This work is sufficiently demanding that relatively few scientists do it, and even fewer do it well. The result is that we have a relatively limited database - much more limited than policy makers and the public are aware - on synapse formation and synapse change over the life spans of species. As Patricia Goldman-Rakic reminded me, despite its importance for developmental neurobiology, "this is a sparsely populated field. In fact one might say that the study of postnatal brain development is so sparsely populated that it does not really exist as *a field* of scientific inquiry at all."

In 1975, Brian Cragg first documented a phase of rapid increase in synapses, followed by a phase of synapse-elimination in the visual area of the cat brains.8 In the cat, some synapse formation occurs before birth, but Cragg saw that there was a period of rapid synapse formation from eight to 37 days following birth. He observed peak synaptic densities at around the age of seven weeks in kittens. There followed a protracted "pruning" phase, during which synaptic densities and related neural measures decreased to adult levels. From the peak values, Cragg saw a 40% decrease in average synaptic density and a 29% decrease in the average number of synapses per neuron.

Two years later, Jennifer Lund and her colleagues reported a similar pattern in the development of the monkey visual cortex.9 They reported that synapses peaked at around eight weeks of age in the monkey. From eight weeks, but continuing through at least nine months of age, there was a gradual reduction until synapses stabilized at adult levels. From these early studies, neuroscientists concluded that, at least for the brain's visual area, there is an early developmental phase, during which the rate of synapse formation exceeds the rate of synapse elimination. This is followed by a second phase, during which the rate of synapse elimination exceeds the rate of synapse formation.

Although Cragg, Lund, and others documented this phenomenon, they were cautious in interpreting their discovery. Like archeologists who had just stumbled upon Stonehenge, they could describe their find in some detail but knew it would take more time and study to figure out what their discovery meant. Their studies assessed neither how changes in synaptic densities affected an animal's ability to see nor how synaptic change contributes to the functional maturation of the visual system.

They did raise an interesting idea that has remained part of neuroscientific theorizing but that has been largely lost in the popular discussion of brain development. They suggested that the *loss* of synaptic contacts might be an important and positive aspect of brain development. "It is perhaps important to realize," Lund concluded, "that the elimination of contacts may be as selective and as constructive towards the final function of the visually altered neuron as the formation of specific synaptic contacts."10

By the 1980s, other researchers began to study the pattern and timing of synapse formation in monkeys and humans. Unlike Cragg's and Lund's initial studies, these later studies looked at various areas of the brain's cortex, not just the visual area. Some of the best work of this kind has been done on brain development in rhesus monkeys by Pasko Rakic, Patricia GoldmanRakic, and their colleagues.11

The gestation period for rhesus monkeys is around 165 days, and the first cortical neurons form 40 days after conception. All the monkeys' neurons are formed over the next 60 days, and the process is complete 65 days before the monkeys are born. Rhesus monkeys (unlike humans) reach sexual maturity at age 3. In their studies, Rakic and his colleagues used animals that ranged in age from a few days postconception to mature 20-year-old adults.

In these animals, Rakic and his colleagues Jean-Pierre Bourgeois and Nada Zecevic examined developmental changes in synaptic densities in the visual area and three other brain areas: the somatosensory area involved in the sense of touch, the motor area involved in movement, and the prefrontal cortex involved in some memory tasks, planning, and other higher brain functions.

In all four areas of the monkey brain, they found the same general developmental pattern. First, there was a period of extraordinarily rapid increase in synaptic density. This period of rapid increase began two months prior to birth. At birth, infant monkeys' synaptic densities were approximately the same as the densities found in adult monkey brains. Synaptic densities continued to increase rapidly, peaking at age 2 months in all areas except the visual area, which peaked at 3 months. The peak densities were twice those seen in adult monkeys. Densities remained at this high plateau level until around age 3 years, the age of sexual maturity. At age 3, synaptic densities began to rapidly decrease, finally stabilizing at adult levels at age 4 to 5 years. The single exception to this pattern was the prefrontal area. There, rather than a rapid decline following the onset of puberty, there was a slight but significant decline in synaptic density starting at age 3 that continued throughout the monkeys' lives.

Further analysis of their data caused Rakic and his colleagues to conclude that decreases in synaptic density were due to genuine synapse elimination in the brain, not to the number of synapses remaining constant while the brain grew in volume. The rate of synaptic loss is staggering. In the monkey, over a period of 2 to 3 f years, 2,500 synapses disappear every second from the primary visual area in each brain hemisphere. 12

This research confirmed that a rapid increase followed by a decrease in synaptic density occurs throughout the rhesus monkey brain and is not confined to the visual area, as had been known since Lund's study.

The work of Peter Huttenlocher and his colleagues at the University of Chicago has revealed that a similar pattern occurs during human development, but on a different time scale. Of course this is no surprise, because monkeys and humans have very different life spans. Monkeys mature sexually at 3 years and are old at 20. Humans mature sexually early in their second decade and live another 60 to 70 years.

Over the past two decades, Huttenlocher's research group has been one of the very few that have studied changes in synaptic density over the human life span. They have counted synapses. In around 50 human brains, looking at three brain areas. These brains were obtained at autopsy from patients ranging in age from 28-week-old fetuses to 90-year-old adults. Although 24 of the brains were from children in the prenatal-to-3-year age range, *only three* of the brains were from children between 4 and 1 I years old, an important period in brain development for which we would like to have more data. Huttenlocher has reported results from three such studies in four research papers.13

In a 1979 paper, Huttenlocher reported results on changes in synaptic density over the life span in the frontal area of the human brain. He found that at birth infants have synaptic densities that are nearly the same as those found in adults. He found a rapid increase in synaptic densities between birth and age t year. Synaptic density peaked in the frontal cortex at around 1 to 2 years of age, when it was 50% higher than average adult values. Between the ages of 2 and 16 years, densities declined to mature levels and remained there throughout adulthood. Using data on changes in brain volume with age, Huttenlocher, like Rakic, argued that the decline in synaptic density could not be accounted for by a stable number of synapses confined within a growing brain. At age 7 years, the human brain has nearly reached adult volume, but synaptic density is still 36% higher than in adults. Thus the decreases in density must be due to a relative loss of synapses during development. He concluded: "This finding confirms the fact that synaptic density in mammalian cerebral cortex declines late in development, after brain growth is nearly complete."14

In 1982 and 1987 publications, Huttenlocher reported changes in synaptic densities over the life span in the human visual cortex. Again, at birth, synaptic densities in this brain area were near adult levels. Densities increased most rapidly between 2 and 4 months of age and peaked between 8 and 12 months of age at levels 60% higher than those seen in adults. In the visual area, there was then a longer period of decreasing density extending beyond 3 years of age, stabilizing at adult levels at around age 11.

In his most recent published study, Huttenlocher looked at two brain areas - the frontal cortex (the same area studied in the 1979 paper) and the auditory cortex in the same human brains. He found that synaptic density peaked in the auditory cortex at around 3 months of age, but that it did not peak in the frontal area until around 3.5 years, a later peak than he had found in his 1979 study. This suggested to him that synaptic development in the frontal area lags behind that in the auditory area. Synapse elimination also appeared to be on different timetables in the two areas. Synapse elimination appeared to be complete by age 12 years in the auditory cortex, but it continued in the frontal area until mid-adolescence. Huttenlocher did point out, however, that his conclusions on rate of elimination were only

Bracket

tentative because he had only *four adolescent brains* in the study, and these showed considerable variability.

The Rakic and Huttenlocher data figure prominently in developmental neuroscience and in the early childhood literature because they present the best direct evidence we have in humans and nonhuman primates on how synaptic densities change over the life span. As I noted, methodological and technical problems can make precise comparisons between studies and across species problematic, yet the research points to striking similarities between rhesus monkeys and humans. First, in both species, synaptic densities peak at around the same absolute level in all brain areas, and final, mature synaptic densities are around 60% of the peak values in all brain areas that have been studied. This suggests, as Rakic and Huttenlocher have pointed out, that there might be a normal range for synaptic density throughout the primate brain. Having either too few or too many synapses might be detrimental to brain function.

The studies also show that in both species there is a three-stage pattern of change in synaptic densities over the life span. What we see from the research is that synaptic densities follow an inverted-U pattern over our lifetimes, as they do over the life span of rhesus monkeys. At birth, we have approximately the same synaptic densities in our cortex that we do as adults. Rapid synapse formation following birth leads to a plateau period during which synaptic densities exceed adult densities. Synapse elimination beginning at puberty reduces densities to adult levels. It will be helpful to keep this inverted-U image in mind as we begin to consider how neuroscientists and Myth advocates interpret what this pattern might mean for behavior, intelligence, and learning.

PET Scans and Synaptic Development

In humans, we also have some indirect evidence that synaptic densities in the brain vary over the life span. A 1987 positron emission tomography (PET) study by Harry Chugani, M. E. Phelps, and J. C. Mazziotta provides this indirect evidence that corroborates Huttenlocher's more direct evidence.15

Brain imaging technologies, like PET, allow neuroscientists to monitor brain activity in living human subjects. PET studies use radioactively labeled oxygen and glucose to measure rates of brain energy metabolism. In human studies, scientists inject these substances into experimental subjects. The blood supply delivers the substances to the brain. The scientists assume that the more active brain areas would require more energy and would use more of the radioactively labeled, energy-providing substances. After a period of time, the labeled substances undergo radioactive decayandemit positrons. (Positrons are subatomic particles that have the same mass as an electron but that, unlike electrons, carry a positive rather than a negative electrical charge.) Positron detectors arranged in a ring around the subject's head detect these emissions and - using some geometry, some physics, and some high-powered computing - scientists can calculate the paths that the positrons traveled. The path data allow scientists to construct images that show which areas of the brain are burning more or less of the oxygen or glucose in response to energy demands.

In their oft-cited work, Chugani and his colleagues report results of PET scans on 29 epileptic children, ranging in age from 5 days to 15 years. These children needed PET scans for diagnostic purposes, so in one sense the children were not totally normal neurologically. We have no PET data (at least none that I have been able to find) from normal children, because PET scans require the injection of radioactive substances that researchers cannot administer to normal, healthy children. Chugani and his colleagues do address this issue, arguing that apart from their epilepsy, the children were otherwise neurologically sound. The researchers compared the epileptic children's scans to those taken on seven young, normal adults, ranging in age from 19 to 30.

In this study, the scientists gave the children radioactively labeled glucose and measured the rate at which specific brain areas took up the glucose. While the scans were being acquired, the scientists made every effort to eliminate, or at least minimize, all sensory stimulation for the subjects. Thus they measured the rate of glucose uptake when the brain was (presumably) not engaged in any sensory or cognitive processing. That is, they measured "resting-brain" glucose metabolism.

Despite this study's popularity and importance, it is a single study of just 29 epileptic children, many of whom had been medicated since infancy and 18 of whom had received medication on the day they were scanned. However, it provides almost the only imaging data that we have from which to make guarded inferences about what might happen during "normal" human brain development.

With these cautions in mind, what did Chugani and his colleagues find- They saw that, during the first year of life, glucose uptake in the infant cortex was between 65% and 85% (depending on the specific brain area) of that found in adult brains. In newborns, the area with the highest metabolic activity was the primary sensorimotor area, the area that supports the infants' sense of touch and bodily sensation. During the second and third months of development, there was a gradual increase in resting metabolic activity in other brain areas, such as those associated with hearing and vision. By age 8 months, metabolic activity began to increase in some frontal areas of the brain. At age I year, the anatomical

distribution of glucose uptake in infants' brains had the same qualitative pattern as that found in adult brains. However, the infant rates were still quantitatively lower than the adult rates.

After the first year, the maturational curves for all brain areas followed a similar pattern. In all the areas examined, metabolic levels reached adult values when children were approximately 2 years old and continued to increase, reaching rates twice the adult level by the age of 3 or 4. Metabolic levels remained at this high plateau level until children were around 9 years old. At age 9, rates of brain glucose metabolism started to decline and stabilized at adult values by the end of the teenage years. Like the synaptic densities Rakic and Huttenlocher calculated, rates of brain glucose metabolism follow an inverted-U pattern from birth to early adulthood.

Huttenlocher counted synapses, whereas Chugani and his colleagues measured glucose metabolism. To connect glucose metabolism to synapses, Chugani and his colleagues reasoned as follows. First, based on Rakic and Huttenlocher's work, we know that, in rhesus monkeys and humans, there is initially a vast overproduction of synapses, followed by synaptic loss that continues until early adolescence. What Chugani and his colleagues see in the PET scans, they argue, is consistent with the process of synaptic overproduction and elimination. They cite other evidence to show that synapses and dendrites account for most of the glucose the brain consumes. So, they reason, as the density and number of synapses and their associated neural processes wax and wane, so too does the rate of brain glucose metabolism. Thus what Chugani and his colleagues measured provides an *indirect* measure of what Huttenlocher counted. Changes in measures of glucose metabolism over time are correlated with changes in synaptic density and numbers over time. Chugani and his colleagues also note that there might be other explanations for the pattern they observed.

Chugani's 1987 PET study is one of the all-time favorites in the Myth literature. It is one of those "all things to all people" studies and possibly one of the most over interpreted scientific papers of the last 25 years. Part of the reason for this is our fascination with brain images. Imaging studies have assumed a central but problematic role in how the public understands the brain.

We are fascinated and mystified by how the brain functions. But until recently we have not been able to "see" a living, functioning human brain "in action." Vividly colored pictures that purport to show the brain actually perking or bubbling along give us concrete images of what before we had thought of as hidden and mysterious processes. Before brain imaging, the brain was indeed a "black box" for most of us.

We should not forget, however, that PET images of a brain are not Polaroids. They are images that represent complex data after considerable statistical processing and enhancement. Our brains are not red when we look at an intense black-and-white checkerboard and blue when we close our eyes. The colors represent increases and decreases in brain metabolism or cerebral blood flow over some baseline level. Far from being Polaroids, brain images are difficult to acquire and even more difficult to interpret, even for the experts.

Nonetheless, Chugani's PET study is taken as the paradigmatic example of how neuroscience is now providing "hard data" about the importance of the first three years of life.

According to *Starting Points*, new neuroscientific research showing that "the brain development that takes place before age one is more rapid and extensive than we previously realized" underscores the importance of the first three years of life. The report cites Chugani's study as evidence for this claim.16

Rethinking the Brain further elaborates on the significance of this imaging study, emphasizing the changes in the brain's metabolic activity during the first year of life: "Cortical activity rises sharply between the second and third months of life - a prime time for providing visual and auditory stimulation. By about eight months, the frontal cortex shows increased metabolic activity. This part of the brain is associated with the ability to regulate and express emotion, as well as to think and to plan, and it becomes the site of frenetic activity just at the moment that babies make dramatic leaps in self-regulation and strengthen their attachment to their primary care givers."17 This is the period, according to *Rethinking*, when parents and caregivers can most help infants develop self-regulatory skills.

The interpretations of Chugani's PET study that these policy documents offer are, to be kind, highly convoluted and go well beyond the evidence presented in the original scientific paper.

Let's just consider the passage quoted from *Rethinking the Brain*. If you look at the published data, it is not the case that cortical activity rises sharply between the second and third months of life. It is more accurate to say, as Chugani does, that one can observe increases in glucose metabolism in various cortical areas at that time. Where there was at 2 months of age very low metabolic activity in the cortex, at 3 months, there is more metabolic activity -nothing so dramatic as a sharp rise. Similarly, the frontal cortex is not "frenetic" at 8 months; rather, its rate of metabolic activity increases to levels comparable to other brain areas. One might say it begins to come "online" at 8 months. It is not clear what the rationale is for thinking that the PET results give reasons for providing visual and auditory stimuli at age 2 months

Bracket

and self-regulatory training at 8 months. Although the frontal cortex might come online at 8 months, it will not mature, at the synaptic level, until puberty, no matter what kind of stimulation a parent might provide.

A PET study showing when brain areas come online metabolically or a neuroanatomical study that shows when synaptic densities increase does not speak to when, or even to whether, parents might be able to "train" brain areas. The simple fact is that, although we know these events occur, we do not know what they mean for child development or to what extent, if at all, environmental and parental stimulation affects these events.

More interesting, however, is that Chugani and his colleagues do not interpret their PET study as indicating that birth to age 3 is the most important period for parents and caretakers to have an impact on brain development. In their original paper, they conclude that "our findings support the commonly accepted view that brain maturation in humans proceeds at least into the second decade of life."" For Chugani, however, it is the plateau period of high metabolic activity and high synaptic connectivity - the years from 3 to 8 or 9 - that is most significant developmentally.19 It is during this developmental period, Chugani consistently claims, that experience fine-tunes neuronal circuits and makes each individual's neuronal architecture unique. Of course, this too is an interpretation that goes beyond the data he presents in the PET study.

What we must always keep in mind is that this PET study is important because it corroborates, using indirect evidence, the existence of the inverted-U pattern that Huttenlocher documented with more direct evidence based on counting synapses. What that pattern might mean for child development and parenting is a substantial, difficult question that is not adequately addressed in either Chugani's original article or in the discussions of early synapse formation in documents like *Starting Points* and *Rethinking the Brain*. What might current neuroscience contribute to answering this question-

Digging Beneath the Metaphors: Neuroscience, the Myth, and Synapse Formation

The neuroscience we have just reviewed plays a fundamental role in the Myth literature. Policy and popular descriptions convey this neuroscience via the neural crackling and zapping metaphors that link early brain development, particularly rapid synapse formation, with the amount and quality of stimulation infants receive during their first years of life. Now that we have a better understanding of what the relevant neuroscience says, we can better assess the extent to which the science supports the ideas and images that the Myth conveys about early brain development. Three Myth claims in particular are based on the phenomenon of early, rapid synapse formation, which is the Myth's first strand.

First, the Myth literature maintains that this period in development is crucial because it is the time during which most synapses form and that the more synapses we have, the more intelligent we are. One often sees claims in the popular birth-to-3 articles that more synapses mean more brainpower. The Myth suggests that the reason why we should talk, sing, and read to an infant is to stimulate the baby's brain, thereby facilitating synaptic growth. This increases the infant's brainpower, thus building a better brain than the baby would have otherwise. More synapses are better than fewer. "The evidence indicates," we read, "that the more connections you have, the smarter you are." 20

Second, there is a claim that early environmental stimulation *causes* synapses to form. According to the Education Commission of the States, the early years are developmentally crucial because "brain connections develop especially fast in the first three years of life in response to stimuli, such as someone talking to, singing to, reading to, or playing with the infant or toddler."21 In *It Takes a Village*, we are told that "with proper stimulation brain synapses will form at a rapid pace, reaching adult levels by the age of two and far surpassing them in the next several years." And according to *Inside the Brain*, "Growing evidence indicates that early mental stimulation promotes the growth of synaptic connections between brain cells."22 Another article tells us that "the more experience or stimulation that an infant undergoes, the more brain connections are made." 23

Third, there is a claim that the period of rapid synapse formation is the time during which basic learning skills are "hardwired" and that somehow this process ends when the period of rapid synapse formation ends. Joan Beck, the *Chicago Tribune* columnist, tells us that, during the first three years of life, "the brain grows most rapidly and then becomes hard-wired into an organ of thinking." What happens, she concludes, during the first three years -- the time of rapid synapse formation, the only time we have to build a better brain -- affects the child for the rest of its life.24

Let's look at each of these claims individually.

Neural Accounting: Brainpower And Synaptic Density

The Myth propagates a profound misconception about the relation between synapses and "brainpower" and what neuroscientists know about that relation. The misconception is that there is a linear relation between the number of synapses in the brain and brainpower or intelligence. More simply, the Myth

Bracket

literature suggests that more synapses equal more brainpower. This misconception contributes to both the popular and policy appeal of the Myth.

It allows us to think about brain development and intelligence in a concrete, quantifiable way. We come to believe that we can measure our success as parents, caregivers, or teachers by doing a little neural reckoning. Seductive as this view might be, the neuroscientific evidence we have does not support it. Whatever the relation is between synapses and brainpower, it is not a simple one.

The neuroscientific findings on humans and animals show, as we have seen, that synaptic density follows the inverted-U pattern -roughly, low, high, low - from birth through childhood to adulthood. However, none of the studies looked at whether monkeys or humans with more synapses or with higher resting rates of brain metabolism were smarter. Data like Rakic's, Huttenlocher's, and Chugani's do not speak to this issue at all, and there are no reliable data that do.

However, there have been a few cases in which researchers have studied defective brains. People suffering from the genetic disorders that cause Down's syndrome or Patau's syndrome do have brains with abnormally low synaptic densities. As early as 1975, however, neuroscientists also had found cases of human mental deficiency in which the patients' brains had abnormally high synaptic densities.25

More recently, Huttenlocher reported a case of a mentally defective child whose brain had synaptic densities higher than those found in normal patients.26 He speculated that patients whose brains had undergone developmental arrest at an early age would likely have abnormally high synaptic densities as adults and not be the better off for it. Again, following the theme first enunciated by Lund in the mid-1970s, synaptic loss is fundamental to normal brain development. At the synaptic level, normal brain development may be a regressive, rather than a progressive, process. Creating more synapses or preserving as many of them as we can into adulthood may be neither possible nor desirable. Although the phrase "use them or lose them" is a popular one in discussing synapses and the brain, it gives a misleading overall description of what goes on during normal brain development. It tends to conceal the fact that losing synapses is also part of the maturation process for our brain circuitry and that such loss is normal, inevitable, and beneficial.27

Recent research on fragile-X syndrome also suggests that too many synapses are detrimental rather than beneficial to efficient mental functioning. Fragile-X syndrome is the second most common form of mental retardation in humans after Down's syndrome. It affects approximately one in 2,000 males and causes severe mental and behavioral impairments. Mature brain tissue removed from fragile-X patients at autopsy contains long, thin, twisted postsynaptic spines that resemble the spines seen during early brain development. Synaptic densities are also higher than normal in these tissue samples. Scientists have constructed an animal model of fragile-X in a strain of genetically altered mice. Brain tissue removed from these mice shows the same twisted dendrite structures and higher than normal synaptic densities that are found in the human samples. In adulthood, fragile-X mice have more synapses than do normal mice. Fragile-X syndrome may result from a developmental failure that prevents synaptic maturation and proper synapse elimination during development. With fragile-X, more is indeed less.28

One final, commonsense reflection on the inverted-U pattern should convince us all that more synapses do not necessarily mean more brainpower. Synaptic densities follow an inverted-U pattern, but our intellectual capacities and ability to learn do not. At birth and in early adulthood, synaptic densities are approximately the same. However, by any measure one cares to use, adults are more intelligent, have more highly flexible behaviors, and show capacities to learn subject matter and reasoning skills that we do not see in infants, toddlers, and 3-year-olds. Furthermore, the late adolescent and early adult periods of rapid synaptic loss do not result in a drop in brainpower. Despite what many parents might express about the difficulties of having teenagers in the house, the problem that parents confront is not that their teenagers become rapidly less intelligent as they leave junior high school and enter high school. They may be emotionally and temperamentally difficult, but as massive synapse elimination begins at puberty, adolescents are just beginning a stage in their lives during which they have the ability to learn and master diverse, complex, and abstract bodies of knowledge. Based on observed behavior, measures of intelligence, and our ability to learn, there is no clear connection between synaptic densities or synaptic numbers and brainpower.

Goldman-Rakic summarized what she and many brain scientists believe, given the evidence they currently possess, about the relation between early synapse formation, learning, and intelligence. As she told the participants at a Denver meeting sponsored by the Education Commission of the States: "While children's brains acquire a tremendous amount of information during the early years, most learning takes place after synaptic formation stabilizes. From the time a child enters first grade, through high school, college, and beyond, there is little change in the number of synapses."29 It is during the time when no, or little, synapse formation occurs that most learning takes place.

While neuroscientists believe that there is some relation between brain connections and intellect, they are still trying to discover what that relation might be. Based on their studies of synapse formation and

elimination in nonhuman primates and in humans, neuroscientists like Huttenlocher and the Rakics draw a cautionary conclusion. In a 1986 article, Goldman-Rakic wrote, "Although neuroscientists believe that the ultimate explanations of behavioral phenomena will come from an understanding of cell-to-cell communication at the synaptic level, at the same time, no one believes that there will be a simple and linear relationship between any given dimension of neural development and functional competence."30 That is, despite what we read in the papers, the neuroscientific evidence does not support the claim that the more connections you have, the smarter you are.

Making Synapses Grow: Stimulation and Early Brain Development

The Myth literature also conveys a misconception that early environmental stimulation or experience *causes* synapses to form. This, too, runs counter to the existing neuroscientific evidence. Rather, the research suggests that genetic and developmental programs, not environmental input, control early synapse formation.

Data from several species, including humans, show that environmental input does not *initiate* rapid synapse formation. Rapid synapse formation begins in the visual cortex of a rat about two days after birth and increases rapidly until the rat is around 3 weeks old. However, rats do not open their eyes until they are around 2 weeks old, long after the rapid growth is well under way. Rapid synapse formation begins before the animals have any sensory stimulation from their environments. In the monkey visual cortex, as we have seen, rapid synapse formation begins two months prior to birth. According to Huttenlocher's data, synapse formation also begins in some areas of the human brain before birth. If in these species rapid synapse formation begins before the animals have any sensory input from the environment, then sensory input does not initiate rapid synapse formation.

Furthermore, following birth, environmental input does not appear to drive the process of rapid synapse formation, to cause more synapses to form. Of necessity, evidence for this claim comes from studies done on monkeys.

Somatosensory, or tactile, skills in rhesus monkeys appear very early in their development. At around 2 months, rhesus infants can make tactile discriminations of size and texture with the same precision as adults. This is also the age, based on the Rakic data, at which synaptic densities peak in the monkey somatosensory cortex. Neuroscientists take this correlation as suggesting that, when synaptic densities peak, a critical mass of synapses forms. This critical mass of connections allows brain circuits to come "online," thus allowing the monkey to make the tactile discriminations.

In one experiment, Mary Carlson raised an infant monkey with its right hand restrained in a soft leather mitten.31 The mitten kept the monkey's hand in a tightly fisted position from birth until the animal was over 4 months of age. During that time, the animal received no sensory stimulation to its right hand. Carlson expected that this extended sensory deprivation would retard the animal's ability to make size and texture discriminations. When the mitten was removed, the animal showed some initial, transient impairment, but, to Carlson's surprise, the monkey quickly began to perform at the same levels as normal animals. If a critical mass of synapses is necessary to perform this task, then the monkey possessed that critical mass. It had tactile skills comparable to normally reared animals. Yet the animal's right hand had not received any sensory stimulation for the first four months of its life nor had the part of the brain that would process those stimuli. Therefore, for the tactile system at least, it is not true that stimulation causes synapses to form. The synapses formed in the absence of any stimulation.

A few studies have examined the effects of both sensory deprivation and increased sensory input on the rate of synapse formation and on synaptic density in rhesus monkeys. In the deprivation experiment, researchers removed the retinas from fetal rhesus monkeys during the first half of gestation, around 80 days before the monkeys would normally be born.32 After the monkeys were born, they compared the visual areas of these totally deprived animals' brains with the visual areas of normal, age-matched monkeys. There were some differences. The blind animals had fewer neurons going into their brains' visual areas than the sighted animals, and for that reason, blind animals had smaller visual areas than the sighted animals. However, despite the fact that the experimental animals had been totally deprived of any visual stimulation, there were no significant differences in synaptic densities between the blind and the sighted monkeys. The rate and extent of synapse formation were the same in blind and sighted animals of the same age.

In the increased sensory stimulation experiment, three-week-premature rhesus monkeys received intensive visual stimulation from birth to see if such stimulation could accelerate synapse growth in their visual areas.33 This experiment directly tested the claim that "the more experience or stimulation an infant undergoes, the more brain connections are made." Contrary to the experimenters' expectations, despite all the extra stimulation, the synaptic densities of the preterm, highly stimulated monkeys were no different from those of the full-term, normally stimulated control monkeys.

Together, experiments like these show that the rate of synapse formation and the degree of synaptic density are impervious to the quantity of stimulation - either to deprivation or to overstimulation. Contrary

to what the Myth suggests, early rapid synapse formation appears to be under genetic, not environmental, control. This was clearly stated in one of the most recent scientific reviews of the relation between synaptic change and mental development: "The *developmental* accumulation of synapses (i.e., the phase of early rapid increases in synaptic density] is altered much less by environmental stimulation than has been appreciated or would be expected by conventional wisdom."34

Rapid Synapse Formation and Hardwiring the Brain

Finally, let's consider the claim of the Myth's supporters that it is only during the early years of life that we have the opportunity to "build better brains." The Myth suggests that after the period of rapid synapse formation ends - a period that, based on Huttenlocher's data, ends in the human brain at around 3 to 3.5 years of age - the mechanisms for learning are established, and brain circuits become hardwired. To adequately assess this claim, we will have to look at how behaviors and abilities change during and after the period of rapid increase in synaptic densities.

One of the best examples to consider in assessing this claim comes from a series of studies done by Goldman-Rakic and Adele Diamond, a developmental psychologist. These studies examined how short-term, or working, memory skills develop over the early months of life in both infant monkeys and human infants. Specifically, the researchers studied how monkeys and infants improved on what psychologists call "delayed-response tasks."35

In delayed-response tasks, the experimental subject observes the experimenter hide an object or morsel of food in one of two wells on a tray. The experimenter then obscures the tray from the subject's view for a period of time. After the delay, the subject selects one of the two locations. The task requires that the monkeys or infants remember information about where the object was hidden for a period of time (the delay) and then "find" the object when the only information available to guide the choice is their memory of where the experimenter had hidden the object. To do this, the infant monkey or human must have a mental representation, or a memory trace, of the original "hiding" and the ability to hold that memory "online" during the delay.

Such simple tasks tap into a highly significant mental skill. Delayed-response tasks measure the emergence of representational memory -the ability to create and maintain a mental representation of an event that is no longer present to the senses. Representational memory is "a building block, if not cornerstone, of cognitive development in man," according to Goldman-Rakic.36 Furthermore, there are abundant neuroscientific studies, using a variety of techniques and measures, that provide strong converging evidence that this building block of cognitive development is dependent upon a specific part of the monkey brain, the dorsolateral prefrontal cortex. The association between this brain area and the ability to do delayed-response memory tasks is one of the best-established brain/behavior relations in neuroscience. This allows us to compare improvement on delayed-response tasks with changes in frontal brain areas. It allows us to understand how improved representational memory corresponds with changes in synaptic density.

Goldman-Rakic and Diamond regularly tested monkeys and infants on delayed-response tasks, starting when the monkeys or babies could first make reaching movements. When the monkeys were 1.5 months old (the age at which the monkeys could first make reaching motions at the tray), the experimenters began testing them on delayed-response tasks five days per week. Testing continued until the monkeys were around 4 months old. The mark of success on delayed-response memory tasks is the length of delay the animal or infant can tolerate before starting to make incorrect choices. The longer the delay tolerated, the better the ability to hold information "online" in memory to guide the choice.

Infant monkeys first showed an ability to succeed at delayed-response tasks when they were a little less than 2 months of age, tolerating delays of around 2 seconds. By age 2.5 months, they could tolerate delays of 5 seconds and by age 4 months, delays of up to 10 seconds. The young monkeys showed a gradual, constant developmental improvement on these tasks, improving at a rate of around I second per week in the delays they could withstand.

Although Diamond and Goldman-Rakic did not count synapses in these monkeys, one can relate the improvement on the memory tasks to the developmental changes that Rakic and his colleagues found in their studies of frontal areas in the monkey brain. Remember that they found that synaptic density peaks in all areas of the monkey brain at around 2 months. This is precisely the time at which the monkeys began to show their first successes on delayed-response tasks. This suggested to Goldman-Rakic that the first appearance of basic skills and abilities associated with a brain area occurs when synaptic densities, as measured by Rakic, peak in that brain area. Here the ability to form representational memories in monkeys is correlated with the peaking of synaptic densities in the frontal areas of the monkey brains. The pattern seems to be that synaptic densities increase under genetic control, and, when they peak, the associated skills and behaviors first appear in elementary form.

We can tell the same, although a bit more complicated, story about the emergence of representational memory in human infants. Diamond tested infants on delayed-response tasks every two weeks starting

at around 6 months (the age at which babies could first make reaching movements toward the tray). She tested the infants once every two weeks until they were 12 months old. Infants first started to succeed at delayed-response tasks at delays of up to 2 seconds when they were around 7 months of age. The infants improved on the tasks at a rate of about 2 seconds per month, until at age 1 year, they could tolerate delays of up to 10 seconds. What happens to the monkey's representational memory abilities between 2 and 4 months of age occurs in the human infant over the period of 7 to 12 months.

Using Huttenlocher's data, we can also relate improvements in the infants' representational memory abilities to development of the frontal areas in the human brain during the second half-year of life. However, to compare accurately the monkey and human data, we must first deal with one complication. Earlier, I mentioned that neuroscientists differ in the assumptions and methods they use to calculate synaptic densities and that this can complicate direct comparisons across studies and across species. This is true for the Rakic and Huttenlocher studies.

In his human studies, Huttenlocher computed the number of synapses per unit of whole cortical tissue, including the neural tissue as well as blood vessels, glial cells, and nonneuronal cells and spaces. In the monkey studies, Rakic computed synapses per unit of neuropil - that is, whole cortical tissue, less blood vessels, glial cells, and nonneuronal cells and spaces. Thus Rakic and Huttenlocher used different denominators in computing densities. Different denominators matter because the different kinds of brain tissue included in the denominator grow at different rates during development.

Using his original whole brain tissue denominator, Huttenlocher found that synaptic densities peaked in the frontal areas of the human brain at around 3 years of age. However, when he recomputed his data for the frontal area using neuropil as the denominator (thus making his data more readily comparable to those of Rakic), he found that synaptic density peaked in the frontal area of the human brain at around 7 months of age.37 Goldman-Rakic and Diamond found that 7 months is the age at which human infants can first reliably succeed at delayed-response tasks. Thus, in both infant monkeys and human infants, representational memory abilities first appear when the number of synapses per unit of neuropil in the associated brain area reaches peak value.

The Diamond and Goldman-Rakic studies also provide some additional insight into how experience contributes to improved representational memory skills. In addition to the group of infants that they tested biweekly, they had another group of infants, ranging in age from 2 months to 12 months. They tested each of these infants only once on a delayed-response memory task. This allowed them to determine if improvement on the memory task might be due to practice. It allows us to consider whether experience or increased stimulation affects the development of basic representational memory.

Diamond and Goldman-Rakic found that there was no difference in performance on delayed-response tasks between 9-month-old infants tested once at that age and 9-month-old infants who had been tested every two weeks. That is, infants who had already been tested at least 10 times by age 9 months did no better than 9-month-old infants doing the task for the first time. They also found that the same rate of improvement - about 2 seconds per month in delays tolerated - occurred in infants from all social classes.

In a later study, Diamond did find that over a variety of ages, infants who were repeatedly tested could tolerate delays 1.5 to 2 seconds longer than infants of the same age who had been tested only once. However, she also found that the advantage for the repeatedly tested infants disappeared by the time the infants were 12 months old. Together these findings suggest that representational memory develops at approximately the same rate independent of practice or exposure to the task and independent of any class-related differences in early childhood experience.

When neuroscientists attempt to interpret their findings on rapid synaptic development in behavioral terms, they tend to list examples that exactly parallel the case of representational memory. In monkeys, synaptic density peaks in all cortical areas between 2 and 3 months of age. At around 2 months of age, infant monkeys can make precise tactile discriminations of size and texture (a sensorimotor function). They begin to visually track small objects, reach for objects guided by vision, and visually discriminate objects (visual functions). They show some ability to use individual fingers independently (a motor function). So, the argument goes, in the monkey, all these behaviors emerge between 2 and 3 months of age, at exactly the time when synaptic densities peak throughout monkeys' brains. In interpreting the human data, neuroscientists such as Huttenlocher and Chugani allude to the correlations between synapse change and behavior found in monkeys. Then they argue by analogy that the same is probably true for infant humans, citing a few additional examples of language development that are unique to humans.

Neuroscientists also generally agree that this relationship between first appearance of a skill and peak synaptic density is only a part of the story. Skills continue to improve and behaviors continue to become more sophisticated long after rapid synapse formation ceases and well into the synaptic plateau period. Sensory, motor, visual, and memory skills continue to develop in the monkey, some reaching mature

Brackets

levels only at sexual maturity, when synaptic densities start to decline. The same is true for humans. Among primates, both humans and monkeys, childhood and adolescence -- the plateau period for synaptic densities is a time of massive learning and rapid behavioral change, when adult-level skills emerge in language, mathematics, and logic. On delayed-response tasks, adult monkeys can tolerate delays of two minutes or more. Adolescent children and adults are able to tolerate delays of hours if not days, in addition to developing other sophisticated representational memory skills. The circuitry we need to do these things is not complete, hardwired, or permanently fixed during early development. It is not limited to the time when synapses form most rapidly.

The Synaptic Preservation Strategy

There is one other subtle wrinkle about early synapse development that I should address. According to Huttenlocher's data, the period of rapid synapse formation in the young human brain appears to end at around 3 years of age. The neuroscientific data suggest that environmental stimulation neither initiates this process nor causes more synapses to form. However, this leaves open the possibility that early experience might strengthen existing synapses and that these strengthened synapses would be more likely to survive through the high-plateau period and into adulthood. In this view, building better brains is best accomplished via an aggressive synaptic preservation strategy. We talk, sing, and read to babies to save synapses from elimination, not to cause synapses to form in the first place. In some of the early childhood discussions, we read that the brain "ruthlessly prunes" synapses that have received inadequate stimulation prior to puberty. This line of reasoning suggests that building optimal brains requires that we use as many synapses as possible before puberty or lose them for sure afterward. The more you use, the fewer you will lose.

Chugani has both offered and encouraged this interpretation of his PET study. According to a Wayne State University article on his work, "The trick . . . is to keep desired connections alive and permanent to allow for efficient processing of a variety of functions."38 In an academic review of his own work, Chugani wrote, "The individual is given the opportunity to retain and increase the efficiency of connections that, through repeated use during a critical period, are deemed to be important, whereas connections that are used to a lesser extent are more susceptible to being eliminated."39

Rethinking the Brain makes the same argument:

As pruning accelerates in the second decade of life, those synapses that have been reinforced by virtue of repeated experience tend to become permanent; the synapses that were not used often enough in the early years tend to be eliminated. In this way, experiences - positive or negative - that young children have in the first years of life influence how their brains will be wired as adults.40

Thus the strategy for optimal brain development is to stimulate as many synapses and circuits as much as possible during the period of high connectivity in order to mitigate the effects of the imminent, ruthless pruning at puberty. So, the argument goes, we should engage in an aggressive program of synaptic conservation with our children. We should provide experiences and environments that promote, as the Bee Gees might describe it, neural staying alive.

Superficially, this strategy makes sense, but there is no neuroscientific evidence to support it. First, neuroscientists have little idea how experience before puberty affects either the timing or the extent of synaptic pruning. Scientists - Rakic, Goldman-Rakic, and Huttenlocher among them - have documented that pruning does occur at puberty. None of the studies we have, however, compared differences in final adult synaptic densities with differences in an individual's experiences before puberty. Neuroscientists do not know, for monkeys or humans, whether early experience increases or decreases synaptic densities or synaptic numbers after puberty. They do not know if prior training and education affect either loss or retention of synapses at puberty. They do not know what kinds of synapses - excitatory versus inhibitory - are selectively pruned. Nor do they know whether the animals with greater densities in adulthood (pathological conditions like fragile-X syndrome aside) are necessarily more intelligent and developed.

Some neuroscientists are frankly puzzled about this synaptic preservation strategy. When I asked Bill Greenough about the soundness of such a strategy, he replied, "The evidence strongly suggests that excess connections need to be removed to establish normal function."

David Lewis, a neuroscientist at the University of Pittsburgh, studies the development of the prefrontal cortex in monkeys, a brain area that undergoes considerable reorganization at puberty. The prefrontal cortex contains discrete stripelike clusters of axon terminals. During puberty, the stripes shrink dramatically in size, and some disappear entirely. Lewis believes that these changes occur because axon terminals containing excitatory synapses are eliminated during puberty. This change, Lewis hypothesizes, produces modifications in how the prefrontal cortex processes information.41 Fewer and smaller stripes after puberty may give the adult animal a more focused, restricted, and sustained neuronal response to the stimulus that the animal must remember during the delay period. Our improved performance on delayed-response tasks that occurs throughout puberty might depend on eliminating

Bracket

axons and their associated excitatory synapses, rather than preserving more of them. Pruning is normal. Less is more.

Reflecting on his studies, Lewis thought that the synaptic preservation argument presented an "interesting interpretation" of the little we do know about the pruning that occurs at puberty. He would argue, however, that pruning or eliminating synapses is critical to achieving mature levels of cognitive ability. As he points out, working memory capacity in monkeys progressively improves as pruning in the prefrontal cortex proceeds, and it reaches mature levels only when pruning ends.

Despite its initial, intuitive plausibility, this synaptic preservation strategy does not make much neuroscientific sense. Any plausibility the strategy has derives from our desire to understand the mind and intelligence in terms of synaptic numbers and densities. A neural accounting approach gives us a concrete, quantitative measure for something that we otherwise find abstract and mysterious. Once we buy into the quantitative neural accounting image, it is natural to think that more is always better. Unfortunately, the brain -- at any age -- is more complicated than that.

The First Strand Unraveled

Neuroscientists have made astounding progress over the past hundred years in their quest to understand how, as Kandel and Schwartz said, "behavior depends on the formation of appropriate interconnections among neurons in the brain." They also realize that, despite a century of research, they remain closer to the beginning than to the end of this quest. Making the connection between behavior and synapses remains more of a neuroscientific Holy Grail than a set of commandments engraved on stone tablets. Neuroscientists engaged in this work are more like Lancelot than like Moses. This is not to demean the neuroscientific enterprise, but rather to emphasize the difficulty of the task.

Neuroscientists who study how the brain's fine structures - neural circuits and synapses - govern human behavior and cognitive capacity take justifiable pride in their progress and are rightly optimistic about the future of their science. Yet they are appropriately cautious in interpreting their work, emphasizing that much remains to be done before we can use the research to support specific policy-relevant claims about parenting, child care, and education. As Huttenlocher acknowledges, "The persistence of exuberant synaptic connections during early childhood raises the question whether these connections may be of functional importance for the emergence of cognitive functions in the young child, and for compensation of the child's brain focal injuries. Answers to these questions are not available at the present time." And as Pasko Rakic states, "The connections between neuroanatomy, neurochemistry, and neurodevelopment on the one hand and behavioral research in cognition on the other are rather tenuous."42

The hundreds of thousands of measurements that neuroscientists have made that document a pattern of change in synaptic density in our brains over our lifetimes allow them to generate and support general hypotheses about how synapses support behavior. However, there is still much work to be done before we can move from general hypotheses to formulating and establishing specific relationships between particular changes in the brain and the appearance, acquisition, or learning of specific skills and behaviors. We have every reason to believe that behavior and intellect do ultimately depend, *somehow*, on how brain cells are connected. We are far from knowing *exactly* how the capacity for specific behaviors - such as negotiating a busy street, recognizing a familiar face, understanding a voice-mail message, reading *TV Guide* - or even the development of representational memory depends on specific neural connections.

Goldman-Rakic cautions that every time policy makers, educators, child-care providers, and parents look to brain science for answers to pressing questions, there is a danger and tendency to take what little is known about neural development, accept it uncritically, and interpret it as *the* neural basis of behavior.43 This is what has happened with the little that we know about early synapse formation and modification. This time around, uncritical acceptance and misinterpretation of what neuroscientists do know about these processes taking them as *the* neural basis of behavior -- have given us the first strand in the Myth of the First Three Years.

The neuroscience and its interpretations that I have reviewed here are the basis for a cautionary statement by Carla Shatz: "Much research remains to be done before anyone can conclusively determine the types of sensory input that encourage the formation of particular neural connections in newborns."44

Parents and caretakers should take some solace from this. Brainpower does not depend on the number of synapses formed before age 3. Environmental input, including stimulation provided by parents, neither initiates early synapse formation nor influences when or at what level synaptic densities peak. If the development of representational memory is a suitable example, the brain develops, synaptic densities peak, and elementary behaviors first appear. Rather than this marking the end of the time we have to "build better brains," it seems more likely to mark only the beginning of along developmental and maturational period during which environmental stimulation and experience do matter.