

# Critical Thinking About Critical Periods

edited by

Donald B. Bailey, Jr., Ph.D.  
Frank Porter Graham Child Development Center  
University of North Carolina at Chapel Hill


John T. Bruer, Ph.D.  
James S. McDonnell Foundation  
St. Louis, Missouri

Frank J. Symons, Ph.D.  
University of Minnesota  
Minneapolis, Minnesota

and

Jeff W. Lichtman, M.D., Ph.D.  
Washington University School of Medicine  
St. Louis, Missouri

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## Language Processing

*How Experience Affects Brain Organization*

Helen J. Neville

John T. Bruer

This book presents an opportunity to review what we know about critical periods and brain development in a range of areas, including vision, social-emotional development, and early literacy. One of the challenges confronting scientists is integrating research on these skills and their underlying brain systems to clarify what is and is not known. This chapter discusses research that is directed toward the underlying theme of taking a critical look at critical periods. This chapter focuses primarily on language processing but illustrates general principles of how experience influences brain organization by first summarizing some of the research on perceptual processing. Using this research as a basis, this chapter tries to offer answers to three questions: How do brain systems for perceptual and language processing arise during development? To what degree are these systems tightly constrained by biological factors? What is the role of experience in organizing these brain systems?

Philosophers, educators, and parents have debated issues of development, biological constraints, and the role of experience in development for millennia. These debates are often characterized, in a simple way, as the "nature versus nurture" argument. Systematic research on how and when experience might affect brain development began about 30 years ago with David Hubel and Torsten Wiesel's research on the development of the

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visual system (Wiesel & Hubel, 1965; see Chapter 1). Thus, given this short history, it is not surprising that we do not yet know much about how and when experience influences brain development. Furthermore, until recently most of the research has been on rats, cats, and monkeys. Now, however, with the advent of noninvasive methods for imaging and recording from intact, functioning human brains, we can begin to answer questions more directly about how experience influences human brain development and organization.

Using these new technologies, we would like to answer the following questions: Do different brain systems possess intrinsic constraints that make them able to process certain kinds of information but not others? For example, can the brain's auditory systems only process auditory information, or are there circumstances under which it might come to process visual information? What is the role of environmental input, or experience, in the development and specialization of different brain systems? Is the influence of environmental input on brain systems limited to specific, critical periods in development, or can experience affect brain organization throughout the life span? Are some brain systems subject to critical period constraints, while others are not?

Before presenting the data that address these questions, let us briefly review what is known about the structural development of the brain. By every measure that neuroscientists have used, the human brain does not appear to be fully mature until 15–20 years of age. This holds true if one looks at the size and density of neurons, the extent of dendritic branching, the number and density of synapses, the pharmacological composition of the brain, and the electrophysiological responses of the brain (see Chapter 2). Fifteen to twenty years is a long developmental period during which environmental input could shape brain systems.

Figure 8.1 shows Peter Huttenlocher's oft-cited data on changes in synaptic density in the human brain over the life span (Huttenlocher & Dabholkar, 1997). Using electron-micrographic techniques, Huttenlocher and his colleagues counted the number of synapses in different brain areas in tissue samples taken at autopsy from individuals who died at different ages. These data illustrate that synaptic densities in the human brain change over the life span. Note that the curves depicting these changes do not asymptote, or settle at mature levels, until adolescence, showing the brain's long developmental time course. In every brain area that Huttenlocher studied, he found that there was an early period of rapid increase in synaptic density, followed by a gradual decrease. Maximal synaptic densities in the young brain are typically 50% greater than those found in adult brains. A working hypothesis of many scientists in this field is that this early overabundance of synapses provides the raw material for a mechanism whereby environmental input can shape brain systems. The hypothesis assumes that

**Figure 8.1.** Mean synaptic density in synapses/100  $\mu\text{m}^2$  in primary auditory (open circles), primary visual (filled circles), and prefrontal (squares) cortex at various ages. (From Huttenlocher, P.R., & Dabholkar, A.S. [1997]. Regional differences in synaptogenesis in human cerebral cortex. *Journal of Comparative Neurology*, 387, 170; reprinted by permission.)

environmental input contributes to determining which of the overabundant synapses are maintained or stabilized and which are lost.

An interesting feature of Huttenlocher's data is that the different brain regions he has studied show the same pattern of rapid increase followed by gradual decrease. However, the timing of that pattern follows different developmental time courses in different brain regions. For example, the visual cortex displays the increase and stabilization earlier than the prefrontal cortex, which shows a longer developmental time course. If these data are upheld, they imply that the time periods during which environmental input could shape developing brain systems differ, depending on the maturation of the brain region involved. Thus, we might expect that experience would have its effects on the developing visual system earlier than it would on the developing working memory and attentional systems that are mediated by neural circuitry in the frontal cortex.

The fact that there are different critical or sensitive periods for different brain systems, and even for subsystems within systems such as vision and language processing, is an important message that comes from the data scientists have collected (see Chapters 2 and 3). There appears to be extreme variability in how experience influences the development of different brain systems and their related functions. This is true even within the development of the visual system in which some aspects of development depend on input at one time while other aspects of this system's development depend

on input at other times. For example, the development of ocular dominance preferences has a critical or sensitive period that is different from the period during which visual input can influence a neuron's orientation preference (Mitchell, 1981).

Furthermore, not only are there numerous critical periods within a system like vision or language, but some brain systems and their associated functions change throughout life. Not all systems and functions are subject to critical period constraints. Thus, some brain systems and their related functions are more constrained in their development and depend on receiving specific environmental input at specific times, whereas other brain systems do not. One important research goal is to determine which brain systems are subject to critical period constraints and which are not. These are complex questions. Keep in mind that it makes little sense to speak of *the* critical period for the visual system or *the* critical period for language acquisition. Given what we already know, this is too coarse a picture to guide research and its applications to policy and practice.

It is important to be aware that at the present time we know little about the neural mechanisms that underlie how experience influences brain development, or about the mechanisms responsible for the differences in modifiability by environmental input among brain systems. It is likely that when scientists do uncover these mechanisms they will involve factors such as the early and subsequent loss of excess synapses, changes in the balance of excitatory versus inhibitory connections within and among brain regions, and the degree of redundant connectivity within the brain. However, our current limited knowledge about the specific neural mechanisms involved in developmental brain plasticity does not prevent us from identifying different subsystems within the brain, drawing boundaries between them, and determining when, or if, these systems are subject to critical period constraints. We can identify which systems are changeable by experience and when they are most changeable. These findings will carry implications for the development and implementation of educational and rehabilitation programs.

There are at least two ways to study how experience affects brain organization during development. First, one can look at behavior and brain organization in adults who had different early experiences. For example, adults who have been deaf or blind from birth have had very different early sensory experience from that of hearing or sighted adults. In addition, many deaf people learn a sign language, a visual-spatial language, rather than a spoken, oral-aural language as their first language. Second, one can look directly at the behavior and brain organization in infants and children as they pass through different ages and specific milestones in perception and language.

In the work discussed here, scientists use two noninvasive techniques to study and observe brain organization. In the event-related potential (ERP) technique, scientists record the electrical events generated by neuronal activity in the brain from electrodes placed on individuals' scalps. As a technique, ERP has excellent temporal resolution. It allows them to track brain events rapidly at a millisecond-by-millisecond level. However, ERP's spatial resolution is not precise. Thus, to localize brain activity more precisely scientists use structural and functional magnetic resonance imaging (fMRI), which provides spatial resolution down to the millimeter level and in some cases even to the submillimeter level.

## PRINCIPLES OF BRAIN SPECIALIZATION: PERCEPTUAL PROCESSING

With these research strategies and techniques, scientists have studied both language and perceptual processing. Although the focus of this chapter is on language processing, research on perceptual processing provides a useful model of how experience affects brain development. At the current time, it is reasonable to think, for reasons of scientific parsimony and in the absence of empirical evidence to the contrary, that similar principles govern the development of all highly specialized brain systems.

As mentioned previously, one of these general principles appears to be the variability, even within a perceptual system, in the extent and timing of a brain system's modifiability by experience. Research on visual processing in deaf subjects illustrates this principle. In studies such as these, it is important to have a homogeneous subject population in which we know the etiology of the perceptual problem. All of the deaf subjects who participated in the research discussed here were born to deaf parents and have been profoundly and bilaterally deaf since birth. Their condition is caused by a genetic abnormality that prevents the cochlea from developing normally. So, although they cannot hear because of this defect in the ear, their central nervous systems, including their brains, are not directly affected. The hearing siblings of the deaf subjects provide scientists with a control group. This control group is particularly important in studies of language acquisition, as will be evident in the next section.

Using a subject population like this allows us to ask the following questions: What impact does profound auditory deprivation have on the development of the remaining sensory systems? What happens to the auditory cortex in these subjects? What happens to the visual system when there is no auditory input early in development? We know there is a strong genetic bias for particular cortical structures to process acoustic information. Does this mean that these structures cannot process visual information? Is it pos-

sible to rewire the auditory system to process visual information? Are there limited temporal windows, or critical periods, during which rewiring in deaf subjects' brains can occur? Current research provides interesting answers to these questions.

In studies of visual processing in the deaf, scientists collected ERPs on congenitally deaf people and normal hearing controls as they processed visual stimuli (Neville, 1995). They found that the brain's electrical response to visual stimuli presented in the center of the visual field was the same in both populations. There were no major differences in brain organization after auditory deprivation for processing stimuli in the center of the visual field. However, in response to stimuli presented out in the visual periphery, deaf subjects showed much larger brain activation responses than did their hearing siblings. This finding suggests that auditory deprivation somehow affects the brain's representation of the visual periphery, but not the brain's representation of the center of visual space.

How might we explain this difference? The visual periphery is strongly represented along the brain's dorsal pathway that projects from V1, the primary visual area, up to the parietal cortex (see Figure 8.2). This dorsal visual pathway is important for processing motion and location in space. The center of the visual field is most strongly represented along the ventral visual pathway. This pathway is important for color and form perception. Comparing the brain activations of deaf subjects with those of their hearing siblings suggested the hypothesis that motion and spatial location processing are more plastic or more modifiable by experience during development than are color and form processing.

Scientists designed an experiment to directly test this hypothesis. They presented subjects with one set of stimuli designed to activate the motion sensitive dorsal system and another set of stimuli designed to activate the color sensitive ventral system. They found that deaf and hearing subjects had similar ERP brain response patterns to the stimuli that changed color and activated the ventral visual pathway. However, in response to the stimuli that displayed motion and activated the dorsal pathway, the deaf subjects showed a much larger brain response than did the hearing subjects (see Figure 8.3). From this experiment we can conclude that the ventral visual system was relatively unaffected, whereas the dorsal system was modified, by auditory deprivation. Thus, some parts of the visual system are radically changed after early auditory deprivation and others are not.

Functional MRI studies have allowed us to see more precisely where these changes are taking place in the brain (Neville & Bavelier, 1999). In normal hearing subjects, visual motion activates posterior visual areas and area MT, a motion center in the dorsal pathway of the brain. Deaf subjects have significantly larger activations in these visual areas as well as activations in areas extending up into parietal cortex, frontal cortex, and within

Figure 8.2. The dorsal ("where") and ventral ("what") pathway.

what would normally include the brain's auditory areas. If these results are upheld, they imply that strongly constrained sensory systems can change their functional properties when sensory experience is different.

There also may be a critical period after which rewiring of the sensory systems does not occur. Scientists have studied people who became deaf after the age of 4 due to the same genetic abnormality in cochlear development. In these cases the abnormal gene causes the cochlea to de-differentiate during development. When scientists examined brain recordings of these people who became deaf at a later age, they did not see the same enhanced visual responses to movement. Thus, there may be a limited time, within the first few years of life, when the auditory and visual sensory systems are being organized, during which incoming sensory stimulation plays a role in differentiating and defining these sensory systems.

If the dorsal visual pathway is more modifiable than the ventral visual pathway, then it also may be more vulnerable to abnormal experience. There is substantial evidence in the developmental literature that the dorsal visual pathway is vulnerable. Psychophysical studies (Lovegrove, Garzia, & Nicholson, 1990), physiological studies (Eden et al., 1996), and anatomical studies (Livingstone, Rosen, Drislane, & Galaburda, 1991) of dyslexic children suggest that dorsal pathway functions are deficient in these children, but their ventral visual pathways appear to be intact. Such children have not experienced sensory deprivation, but there is some abnormality in aspects of the visual system's development.

the most vulnerable to abnormal experience. Of course, visual and auditory processing are critical to many aspects of language processing.

### THE DEVELOPMENT OF BRAIN SYSTEMS FOR LANGUAGE PROCESSING

In addition to auditory deprivation, deaf subjects also have had different early language experience. In these studies, the subjects, children of deaf

**Figure 8.3.** ERPs elicited by a) color change and b) motion in normally hearing and congenitally deaf adults. Recordings from temporal and posterior temporal regions of the left and right hemispheres. (From Neville, H.J., & Bavelier, D. [1999]. Specificity and plasticity in neurocognitive development in humans. In M.S. Gazzaniga [Ed.], *The new cognitive neurosciences* [2nd ed., p. 85]. Cambridge, MA: The MIT Press; reprinted by permission.)

Scientists are now using ERPs to study how developing infants and children respond to different sensory stimuli. These studies should reveal the time course of the differentiation and specialization of human sensory systems and provide insight into the neural substrate for sensory plasticity. So, for example, auditory stimuli in adults elicit large brain responses over the temporal cortex but little or no response over the visual cortex (see Figure 8.4). In a 6-month-old child, however, auditory stimuli elicit a large response over both the auditory and visual areas of the brain. This auditory response over the visual areas disappears during development over the period from 6 months to 36 months of age. Based on these studies, the first 3 years of life appear to be a time in development when the sensory systems are becoming organized and when sensory experience can play a role in the organization of these systems.

Studies that look at enhancements and vulnerabilities of systems during development can help us identify systems that are the most plastic and

**Figure 8.4.** ERPs to auditory (speech) stimuli recorded over temporal and occipital regions in normal adults (bottom) and in children ages 6–36 months. (From Neville, H.J. [1995]. Developmental specificity in neurocognitive development in humans. In M.S. Gazzaniga [Ed.], *The cognitive neurosciences* [pp. 219–231]. Cambridge, MA: The MIT Press; reprinted by permission.)

parents, learned American Sign Language (ASL) rather than a spoken language as their first or native language, at the normal age for language acquisition in children. How might this experience affect the development of the brain's language systems? Would deaf subjects show the normal left-hemisphere specialization for language processing that is the ubiquitous pattern in normal hearing people?

There is a possible problem with using deaf subjects to study language processing. The deaf subjects sustained both early auditory deprivation *and* learned a signed, rather than a spoken, language. They have had both unusual early sensory experience and unusual early language experience. It is likely that the two kinds of experiences have different developmental effects on brain organization. How can one sort out which effects are due to auditory deprivation and which are due to learning a sign language? This is where that very important control group comes into the picture: the hearing siblings of the deaf subjects. These children also were born to deaf parents and learned ASL as a first language in early childhood. However, these hearing siblings did not experience any auditory deprivation. Thus, using this control group, we can be confident that the effects on brain organization due to auditory deprivation alone should be observed only in the deaf children and not in the hearing siblings, who are nonetheless "native" signers. Any effects of learning a visual-spatial, rather than an aural-oral, language should be seen in both the deaf subjects and their hearing siblings who used ASL.

As with the work on perceptual processing, the research on language processing attempts to determine whether different subsystems involved in language processing are modifiable by and dependent upon early language experience and whether some aspects of language processing are plastic and capable of change throughout life. Following the distinctions made about language processing by theoretical linguists and psycholinguists, scientists have looked in some detail at two subsystems—semantic processing and grammatical processing.

To study semantic processing, scientists have looked at subjects' brain responses when they process words that carry a lot of semantic and lexical information. Linguists call these words open-class words. They are nouns and verbs that refer to specific objects and events in the world (e.g., dog, banana, dance). We can contrast brain responses to these words with responses to closed class words; words that carry a lot of grammatical information (e.g., if, and, but). A person's inability to use closed-class words—no ifs, ands, or buts—is a clinical test for grammatical aphasia.

Open- and closed-class words are processed by different brain systems (Neville, Mills, & Lawson, 1992). In some ERP studies the subjects process sentences that are either semantically normal but contain grammatical errors (e.g., He gave it Joe to) or sentences that are grammatically correct but

semantically anomalous (e.g., I like my coffee with sugar and cement). Scientists have found that semantic processing is associated with increased brain activity, specifically a negative electrical response over posterior brain regions of both brain hemispheres (see Figure 8.5). In contrast, grammatical processing is associated with increased brain activation over anterior regions of the left hemisphere (Neville, Nicol, Barss, Forster, & Garrett, 1991). Different brain systems mediate these different aspects of language processing.

Researchers have used the sentence processing tasks that place different demands on semantic versus grammatical processes to ask whether people who have learned a language late in life or who have had different early language experience show differences in how their brains process language. Does their different early language experience result in different brain organization for language processing? The answer is, just as with ventral and dorsal visual pathways, both no and yes.

In one study, scientists looked at Chinese-English bilinguals, native Chinese speakers who came to America at different ages (Weber-Fox & Neville, 1996). They found that the brain systems that mediate semantic processing were changed little by delays in exposure to the second language. Native Chinese speakers who learned English between 1 and 3 years of age showed the same normal bilateral brain activation for semantic processing as did native English speakers and as did the native Chinese speakers who learned English between 4 and 6 years and those who learned between 11 and 13 years. Researchers began to see slight differences in the brain responses only in subjects who learned English after age 16. Thus, semantic language processing appears to be invulnerable to delays in expo-

**Figure 8.5.** Processing semantic information in spoken sentences activates posterior areas of both hemispheres while processing grammatical information primarily activates anterior regions of the left hemisphere.

sure to a second language. In this way the semantic system is similar to the ventral visual pathway. Unusual early language experience does not have large effects on how semantic processing is organized in the brain.

However, grammatical processing appears to be more like the dorsal visual pathway. When scientists looked at brain responses during grammatical processing, they found that the Chinese subjects who learned English early, between 1 and 3 three years of age, developed the left-hemisphere activation pattern for grammatical processing just like native English speakers. However, delaying learning until 4–6 years of age resulted in a more bilateral pattern of brain activation. Among the Chinese immigrants who were first exposed to English between 11 and 13 years of age, scientists saw an aberrant activation pattern for English grammatical processing. These results are consistent with the finding in second language learning that later exposure to a second language results in marked deficits in grammatical processing and understanding (see Flege & Fletcher, 1992; see Chapter 10).

We can conclude that within the language processing system, the semantic and grammatical processing subsystems are affected differently by delays in language experience. The grammatical subsystem is more sensitive to early experience than the semantic system.

Researchers have just started to look at phonological processing, another important linguistic subsystem (see Chapter 10). They know that if they hear someone who pronounces English with a nonnative accent that the person most likely learned English after the age of 12. This aspect of phonological processing seems to be subject to a critical period effect. However, it also appears that not all aspects of phonological processing are time limited.

Scientists have looked at the ability to use stress to separate speech into distinct words (Sanders & Neville, *in press*). When we hear a language that we do not know, we cannot tell where one word begins and another ends. One cue we use to segment speech in languages we do know is stress, or the pattern of accent on syllables. In English, for example, the stress rule is strong, then weak: The accented syllable generally precedes the unaccented syllable—NA-tive, ENG-lish, SPEAK-er. We do have some words that show an atypical pattern—per-CENT, cor-RECT, re-CORD. As it turns out, linguists have shown that we can recognize the onset of words that follow the normal stress pattern more quickly than we can recognize the onset of words that follow the exceptional stress pattern.

Researchers have studied native Japanese speakers who came to the United States after the age of 12. These subjects were late English language learners. The Japanese language does not have any stress rules. Nonetheless, the Japanese subjects who learned English late picked up on the English stress rule quickly and showed no limitations in their ability to use stress to segment English speech. Again, we are reminded that there is a lot of

variability in response to early experience, even within a language subsystem such as phonological processing. Some aspects of phonology can be learned with impunity at a later age, whereas other aspects are more constrained within a critical or sensitive period.

Scientists are now doing brain-imaging studies to investigate this phenomenon. For example, they also are looking at people who learned different stress rules—as in Spanish—to see if this rule would interfere with acquiring the English rule later in life.

Now let us return to the deaf subjects and how their unusual early language experience might have affected development of their language processing systems. Deaf subjects' experience with English is different from that of hearing people. For hearing people, English is an aural-oral, spoken-heard, language. For the deaf, English is a visual language, a language they read. Furthermore, when hearing people read they do a grapheme (written symbol) to phoneme (aural symbol) conversion. They convert written symbols into sounds. Obviously, deaf people do not perform this conversion when they read. Also, because most deaf people also learn English relatively late, they learn it imperfectly and often do not fully master English grammar.

How does this experience affect the organization of English semantic processing in deaf people's brains? The short answer is that it has no effect whatsoever. When engaged in semantic processing of English words, both deaf and hearing subjects showed exactly the same brain response pattern. The response has the same latency, amplitude, and scalp distribution in both hearing and deaf subjects. These results are consistent with those described previously in Chinese-English bilinguals' semantic processing. Again, this points to the conclusion that at least some aspects of semantic processing are robust in the face of altered early language experience.

However, when scientists looked at grammatical processing of English sentences in deaf subjects, they did not show the typical activity pattern over the left hemisphere as observed in hearing, native speakers of English. When processing English grammar, the deaf subjects responded like the late-learning Chinese-English bilinguals. This reinforces the conclusion that the grammatical processing system is more dependent upon early experience than is the semantic processing system (Neville et al., 1992).

By studying deaf subjects, we also can gain insight into another question: Why is it, as neuropsychologists have known for more than 100 years, that language processing systems are almost always localized to the brain's left hemisphere? What is the key factor or variable responsible for establishing language-processing systems in the left hemisphere? Is there something special about the left hemisphere with respect to language processing?

There has been a lot of discussion about these questions recently. One hypothesis is that the left hemisphere is the language hemisphere because it is well suited to process the high rates of auditory information that are

typical of language use. In fact, the left hemisphere appears to be good at processing rapid auditory input of any kind, linguistic or not (Merzenich, Recanzone, Jenkins, Allard, & Nudo, 1988; Tallal, Saninberg, & Jernigan, 1991). A second hypothesis is that the left hemisphere is well suited for the grammatical encoding of information that is typical of all formal languages (Lieberman, 1974). Thus, one hypothesis suggests that the left hemisphere is specialized for rapid auditory processing, the other that the left hemisphere is adept at grammatical encoding.

One way to test these hypotheses about left-hemisphere specialization for language is to look at how the brain is organized to process a sign language like ASL. ASL is not auditory and thus does not involve processing high rates of auditory stimulation, but it is highly grammatical (Klima & Bellugi, 1979). Sign language is made with the hands and perceived with the eyes. Both ASL's lexicon and grammar depend on the perception of location in space and movement. A sign language's grammar is temporally coincident with visual-spatial information. Researchers also know that in hearing people the right hemisphere plays an important role in visual-spatial processing. So, how does learning ASL reorganize the brain? Does processing ASL depend on the typical left-hemisphere language systems or, because it is visual-spatial, does it recruit right-hemisphere structures for language processing? Are the left-hemisphere language systems in the brain so constrained that they are used to process any language, regardless of its modality and structure?

To answer these questions, scientists have performed ERP, as well as fMRI, studies on deaf subjects and their hearing, ASL-using siblings (Neville et al., 1997, 1998). In these studies, deaf subjects and hearing subjects looked at written English sentences versus strings of English consonants. Thus, these two experimental conditions presented the same physical stimuli, but in one case the stimuli (sentences) carried linguistic information and in the other case (consonant strings) they did not. Scientists also presented these same subjects with signed ASL sentences versus nonsign gestures, again presenting physically equivalent stimuli, only some of which carried linguistic information.

In the fMRI images of these subjects, researchers looked for particular areas of the brain that were more active when the subjects were viewing linguistic input than when they were viewing the physically equivalent non-linguistic input. Figure 8.6a shows the results for written English. There were three groups of subjects in the study—normal hearing native English speakers; deaf subjects, born to deaf parents, who were native ASL speakers and learned English later in life; and hearing siblings who learned ASL and English early in childhood (control subjects).

For the normal hearing subjects, there were no surprises in the pattern of brain activation that occurred when they processed English sentences. In

these subjects, there was intense brain activity associated with the English sentences in the classical left hemisphere language areas, especially in Broca's area, Wernicke's area, and related posterior-temporal areas. They showed the classic left hemisphere pattern for language processing that many investigators reported in the late 1990s.

When deaf subjects read the English sentences they understood them perfectly well. However, in the fMRIs of the deaf subjects reading English sentences, scientists did not see activation in the classical, left hemisphere language areas. There was no significant activation of Broca's or Wernicke's area and little left-hemisphere activation.

However, they did see considerable posterior-temporal-parietal activation in the right hemisphere when the deaf subjects processed English sentences. Why might this be the case? Is it because deaf people learn a visual-spatial language as a first language, and this establishes a language system in the more visual-spatial right hemisphere? If this were the case, then we should also see this same right-hemisphere activation in response to English sentences in the hearing siblings who also learned ASL as a first language. However, the fMRIs of hearing native signers, in contrast to those of the deaf native signers, showed the typical left-lateralized activation pattern for processing English sentences, with little or no activity in the right hemisphere. So, learning a visual-spatial language as a first language does not account for the right-hemisphere activation and lack of left-hemisphere activation among the deaf subjects.

Maybe the deaf subjects show no left-hemisphere activation to English because for them English is a visual and not an auditory language. Maybe one has to learn an auditory language to organize the left-hemisphere language systems. However, the lack of left-hemisphere activation for English may be the result of having learned English later in life and thus not acquiring full mastery of English grammar. The deaf subjects might be showing the adverse effects of a missed critical period for grammar acquisition.

We can decide among these alternative explanations by comparing brain activation patterns for ASL versus nonsign gesture processing in these three groups of subjects (see Figure 8.6b). The fMRIs of the normal hearing subjects, who did not know ASL, showed no activation differences between ASL sentences and nonsign gestures. This is no surprise. However, when the deaf subjects looked at ASL sentences, scientists saw activation in the classical language centers of the brain's left hemisphere. When deaf subjects process ASL, their brains recruit classical Broca's, Wernicke's, and related areas that are associated with aural-oral language processing. This suggests that these left-hemisphere language centers are well designed and well suited to process formal language, independently of the language's modality or structure. It appears that these brain areas are biologically constrained or determined to process language. Thus, the feature that is special



about the left hemisphere in language processing appears to be its facility at grammatical encoding, and not a facility for processing rapid auditory input.

We see something else quite interesting when deaf subjects are processing ASL. Their fMRIs also show significant activation in right-hemisphere brain areas that are homologous to Broca's and Wernicke's areas, as well as activation along the entire superior temporal sulcus, activations that are not seen in normal hearing people. Do the deaf ASL users show this right-hemisphere activation because ASL is a visual-spatial language that recruits right-hemisphere structures for processing? Or, is this right-hemisphere activation the result of deaf people having hyperactive visual-spatial systems in their right hemisphere? That is, we would like to know whether this right-hemisphere activity is the result of unusual early language experience (learning visual-spatial ASL as a first language) or the result of early auditory deprivation.

Once again the control group of hearing, ASL-using siblings can help answer this question. The hearing siblings did not experience any auditory deprivation in infancy and childhood, but they did have the same unusual experience of learning a language whose grammar relied on temporal coincidences between visual-spatial information and language information. The fMRIs of the hearing siblings showed the same activation pattern as the deaf subjects as they process signed ASL sentences. When processing ASL sentences, the hearing native signers strongly recruit the classical language areas in the left hemisphere *and* the homologous areas of the right hemisphere. Therefore, the right-hemisphere activity seen when native signers (both deaf and hearing) process ASL sentences is an effect on brain organization due to early learning of a visual-spatial language and not due to early auditory deprivation.

In summary, what we learn from this is that when any individual processes sentences in his or her native language, whether English or ASL, the processing always recruits the classical language areas of the left hemisphere. This suggests that there is some biological constraint operating that makes these left-hemisphere structures well suited to process language, if the language is learned early in life. Yet, it also is clear that language experience plays a critical role in shaping the final form of the brain's language systems. We know this from the finding that an individual who learns a visual-spatial language, whether he or she is deaf or hearing, recruits the homologous right-hemisphere brain structures into language processing. There are biological constraints operating on how the brain is, or can be, organized to process language. The left hemisphere seems well suited and constrained to process grammatical information. However, language experience also is critical in determining the final organization of the brain's language processing systems. Clearly, when it comes to brain organization both nature and nurture play fundamental roles.

Given the interest in taking a critical look at critical periods, one might ask: Is there a critical period during development when learning a visual-spatial language recruits those right-hemisphere structures into the brain's language system? Scientists have begun to study this question by looking at people who learned ASL as a second language late in life. They are looking at hearing people who learned ASL after the age of 18 in order to become interpreters for the deaf. When these late learners process ASL, their fMRIs show that they do not recruit the right-hemisphere structures into their language processing systems to the same extent as native learners of ASL (Newman et al., 1998). When they process ASL, they use primarily the classic left hemisphere system. These people can function as interpreters, so they have acquired some fluency in ASL, but they are using different brain systems in processing ASL and are impaired on formal tests of ASL grammar. From these initial studies, it appears as if learning ASL before or after age 18 does make a difference. Scientists do not yet know exactly when this critical period ends, but they can find out by studying people who learned ASL at different ages prior to age 18.

They also have looked at how the language subsystems of the brain develop on-line, during infancy, and during childhood. For the semantic processing system, they study vocabulary development in children. Scientists find that there are shifts during development in how the brain's language systems are configured during the early years of life (Neville & Mills, 1997). These systems do not settle down into mature organization until children are 15 years old. For example, they looked at the children's ERPs when they processed words whose meanings they knew versus words they did not know. There are differences between these two classes of words in children's brain activation patterns. Thirteen-month-old children appear to use widely distributed brain regions within both hemispheres to make this distinction. There is activation of both the left and right hemispheres in frontal, temporal, and parietal regions (see Figure 8.7, top). If one looks at these same children at 20 months of age, quite a shift in the brain activation pattern can be seen. In these older infants, the only brain regions showing a difference for meaningful versus meaningless words is in the left hemisphere, and the difference is confined to the temporal and parietal regions (see Figure 8.7, bottom). This illustrates another general principle of brain development: As the brain develops, there is an increased focalization of the brain activity associated with a processing task. This focalization is an indicator of the increased specialization and fine tuning of functional brain systems.

Note, however, that the increased specialization of the brain systems is not predicted solely by the child's chronological age. We know this from comparing children of the same chronological age who differ in vocabulary size. The 20-month-old children already show this focusing and specialization of the left hemisphere. However, so do 13-month-old children with

ods, early experience, and brain development. The short conclusion is that the effects of early experience on brain development are not as straightforward and transparent as the public has been led to believe, based on discussions of brain science in the policy and popular literature.

There are several principles to keep in mind when reading about critical periods in brain development or in language learning. First, research on how experience affects the brain is in its infancy. New noninvasive imaging techniques will facilitate studies of human brain development. Second, there is variability in how early experience affects brain organization. Some brain systems are subject to critical period constraints and others are not. This variability occurs both within systems such as vision and between systems. Third, within systems in which there are critical periods, these periods can differ for specific subsystems. Given this variability and complexity it makes little sense to speak of a critical period for brain development or even of a critical period for vision or language. Nor would it seem that these periods are limited to the first 3 years of life. Although this research does carry implications for rehabilitation, education, and child development, those implications, like the research itself, may not be straightforward or transparent. As scientists discuss the implications of this work for policy and practice, we must all remind ourselves that children's brains are not hard wired at birth, and that they are not always modifiable by experience either. Future research will identify and characterize the nature and extent of neuroplasticity within the several highly specialized brain systems important for human cognition.

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**Figure 8.7.** ERPs elicited by comprehended and unknown words in 13- to 17-month-old and 20-month-old children. At 13–17 months, ERPs to comprehended words are larger than to unknown words over several areas within both the left and right hemispheres. By 20 months, ERP differences to comprehended and unknown words are limited to temporal and parietal regions of the left hemisphere. (Neville, H.J., & Mills, D. [1997]. Epigenesis of language. *Mental Retardation and Developmental Disabilities Research Reviews*, *3*[4], 282–292; reprinted by permission from Wiley-Liss, Inc., a subsidiary of John Wiley & Sons, Inc.)

comparably large vocabularies. The 13-month-old children who have small vocabularies, however, do not show this focalization specialization. So, while there are maturational changes in the brain that can be defined and that researchers have described, it is clear that language knowledge and experience also play a role in predicting the specialization and differentiation of these brain systems.

## CONCLUSION

The story presented here seems complex and detailed. Nonetheless, the story represents what modern brain science does know about critical peri-

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