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8 Language, Mind, and Brain: Experience Alters Perception

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ABSTRACT How does one individual acquire a specific language? Is it appropriate to call it "learning" in the traditional sense? Historically, two dramatically opposed views formed the cornerstones of the debate on language. In one view, a universal grammar and phonology are innately provided and input serves to trigger the appropriate version. In the other view, no innate knowledge is provided and language is acquired through a process of external feedback and reinforcement. Both theories are based on assumptions about the nature of language input to the child and the nature of the developmental change induced by input. New data reviewed here, showing the effects of early language experience on infants, suggest a theoretical revision. By one year of age, prior to the time infants begin to master higher levels of language, infants' perceptual and perceptual-motor systems have been altered by linguistic experience. Phonetic perception has changed dramatically to conform to the native-language pattern, and language-specific speech production has emerged. According to the model described here, this developmental change is caused by a complex "mapping" of linguistic input. This account is different in two respects from traditional views: (1) Language input is not conceived of as triggering innately provided options; (2) the kind of developmental change that occurs does not involve traditional Skinnerian learning, in which change is brought about through reinforcement contingencies. The consequences of this are described in a developmental theory at the phonetic level that may apply to higher levels of language.

Nature, nurture, and a historical debate

Forty-one years ago, a historic confrontation occurred between a strong nativist and a strong learning theorist. Chomsky's (1957) reply to Skinner's (1957) *Verbal Behavior* had just been published, re-igniting the debate on the nature of language. In Chomsky's (1965, 1981) nativist view, universal rules encompassing the grammars and phonologies of all languages were innately specified. Language input served to "trigger" the appropriate subset of rules, and developmental change in language ability was viewed as biological growth akin to that of bodily organs, rather than learning. In the Skinnerian view, language was explicitly learned. Language was brought about in the child through a process of explicit feedback and external control of reinforcement contingencies (Skinner, 1957).

Both views made assumptions about three critical parameters: (1) the biological preparation that infants bring to the task of language learning, (2) the nature of language input, and (3) the nature of developmental change. Chomsky asserted, through the "poverty of the stimulus" argument, that language input to the child is greatly underspecified. Critical elements are missing; hence the necessity for innately specified information. Skinner viewed speech as simply another operant behavior, shaped through parental feedback and reinforcement like all other behaviors.

In the decades that have passed since these positions were developed, the debate has been played out for language at the syntactic, semantic, and phonological levels. In this chapter, I concentrate primarily on the phonetic level of language, using the elementary components of sounds–the consonants and vowels that make up words–to structure an argument about what is given by nature and gained by experience in the acquisition of language. Studying the sound structure of language allows us to test the perception of language in infants just hours old, addressing the question of what language capacities are innate in infants. Then, by tracking the development of infants raised in various cultures listening to different languages, we can determine, again using tests of perception, when infants begin to diverge as a function of experience with a particular language. These methods provide a strong test of the historically opposing views, and the results of these tests deliver dramatic evidence of the interaction between biology and culture, leading to a new view.

Origins of conceptual distinctions and the modern view

The discussion among linguists and psychologists regarding language is only one forum in which the nature–nurture issue has been debated. Begun by philosophers hundreds of years ago, the nativism–empiricism debate or the nativist–constructivist debate

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concerned the origins of knowledge and whether it stemmed from native abilities or was empirically derived. The debate is of continuing interest across a wide variety of disciplines: ethology (Bateson, 1991; Hauser, 1997), neuroscience (Carew, Menzel, and Shatz, 1998), language science (Kuhl, 1994, 1998a; Pinker, 1994), and developmental psychology (Bates and Elman, 1996; Carey, 1985; Gopnik and Meltzoff, 1997; Karmiloff-Smith, 1995).

These groups use different terms to distinguish complex behaviors that appear relatively immune to, as opposed to wholly dependent on, experience. The terminology reflects differences in emphasis between groups. In ethology for example, the distinction has traditionally been drawn between *innate* or *instinctual* behaviors, considered to be genetically determined, and those *learned* as a function of exposure to the environment (Lorenz, 1965; Thorpe, 1959; Tinbergen, 1951). The emphasis in early ethological writings was on explaining behaviors that existed at birth in the absence of experience (Lorenz's "innate release mechanisms").

In the early psychological literature on the mental development of the child (James, 1890; Koffka, 1924; Vygotsky, 1962), and also in the neuroscience literature (Cajal, 1906), the distinction was drawn using the terms "development" and "learning." *Development* included changes in the organism over time that depend primarily on maturation or internal factors leading to the expression of information specified in the genome. The term development and the term innate are therefore similar, but not identical. *Development* (as opposed to *innate*) emphasized complex behaviors, thought to be under genetic control, that unfold well after birth rather than those existing at birth (innate behavior). *Learning* encompassed processes that depend on explicit experience and produce long-lasting changes. Neuroscientists currently debate how experience alters the brain and whether experience induces *selection*, where options are chosen from a set of innate possibilities, or *instruction*, where experience sculpts a wide open brain (see Doupe and Kuhl's 1999 discussion of birdsong and speech).

Modern writers in all the aforementioned fields agree that behavior unfolds under the control of both a genetic blueprint and the environment, and that the debate now centers on the precise nature of the interplay between the two. Using the development/learning terminology, four alternative models–A through D–can be conceptualized, as illustrated in figure 8.1. The first two are not interactionist accounts, whereas the last two can be described in this way.

Development and learning can be thought of as completely separable processes (figure 8.1, model A). Development follows a maturational course guided by a genetic blueprint, and learning neither follows from nor leads to changes in the pre-established course of development. Alternatively, they can be thought of as two processes so inseparable that they cannot be pulled apart, even conceptually (figure 8.1, model B).

More commonly, development and learning are thought of as separate and distinguishable processes that interact in one way or another (figure 8.1, models C and D). Developmental psychologists, neuroscientists, and neurobiologists largely agree that the interactionist view is the correct one (Bates and Elman, 1996; Bonhoeffer

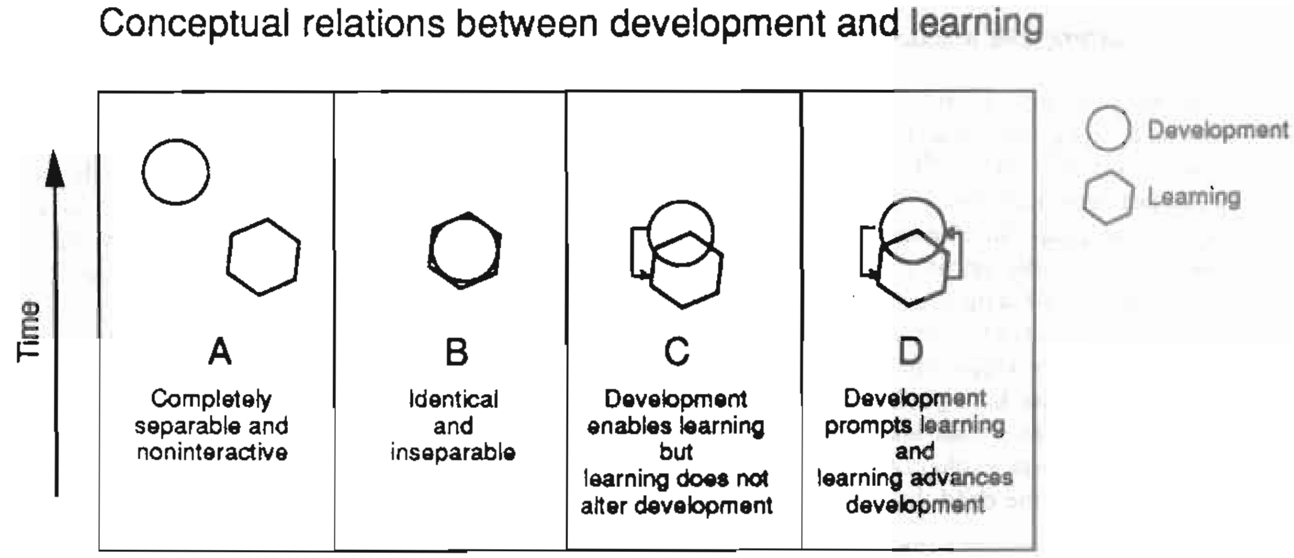

FIGURE 8.1 Conceptual relations between development and learning.

and Shatz, 1998; Carey, 1985; Doupe, 1998; Doupe and Kuhl, 1999; Fanselow and Rudy, 1998; Gopnik and Meltzoff, 1997; Karmiloff-Smith, 1995; Kuhl, 1994, 1998a; Marler, 1990). At issue, however, is exactly how the two systems interact, and particularly whether the interaction between development and learning is bidirectional.

Among the interactionist views, one model is that development enables learning, but that learning does not change the course of development, which unfolds more or less on its own timetable (figure 8.1, model C). Learning is seen as capitalizing on the achievements of development, and cannot occur unless a certain level of development has been achieved. The interaction is unidirectional, however. Development is not affected by learning. In classical developmental psychology, this position is closest to the view of Piaget (1954). In modern neurobiology, the notion that there are "constraints" on learning, that development both prepares the organism and sets limits on learning, is consistent with this model (see Marler, 1974, and Doupe, 1998, for the case of birdsong). Greenough and Black's (1992) "experience-expectant" plasticity, wherein changes in neural development are thought to precede and prepare an organism to react to a reliably present environmental stimulus, provides a detailed example of this model. In each of these cases, development is conceived of as both enabling and limiting learning, but learning does not alter the course of development.

There is an alternative interactionist view. This model describes development and learning as mutually affecting one another (figure 8.1, model D). Development enables and even prompts learning, and learning in turn advances development. This view is closest to that developed by Vygotsky (1979). Vygotsky's theory, the "zone of proximal development" (ZPD), described development at two levels. One was the infant's actual developmental level, the level already achieved. The second was the level that was just within reach. The ZPD was the difference between the two. In Vygotsky's view, environmental stimulation slightly in advance of current development (in the ZPD) resulted in learning and, when this occurred, learning prompted development. Recent theories proposed by developmental psychologists to account for a wide variety of cognitive and linguistic tasks converge on the point that there is mutual interaction between development and learning (Carey, 1985; Gopnik and Meltzoff, 1997; Karmiloff-Smith, 1991).

In linguistic theory, Chomsky's classic view that the growth of language is largely determined by a maturational process fits model C. Experience plays a role, but it is seen as triggering prespecified options or as setting innately determined parameters (Chomsky, 1981). The data reviewed here at the phonetic level of language come closer to the mutual interaction of model D. In the model of speech development I describe, language input plays more than a triggering role in the process. Language input is mapped in a complex process that appears to code its subtle details. Input thus goes beyond setting the parameters of prespecified options. Moreover, early mapping of the perceptual regularities of language input is argued to allow infants to recognize words and phrases, thus advancing development.

In summary, there is a great deal of support for interactionist views (models C and D) over noninteractionist views (models A and B). While the relations between learning and development may differ across species and systems, there is an emerging consensus across diverse disciplines (including neurobiology, psychology, linguistics, and neuroscience) that development and learning are not independent entities. Speech falls clearly on the interactionist side. However, the form of the interaction remains a question, with a cutting-edge issue being whether (and how) learning can alter development. The model proposed here on the basis of recent research on speech development goes some distance toward addressing this issue.

Explanations for developmental change in speech

One of the puzzles in language development is to explain the orderly transitions that all infants go through during development. Infants the world over achieve certain milestones in linguistic development at roughly the same time, regardless of the language they are exposed to. Moreover, developmental change can also include cases in which infants' early skills exceed their later ones. Explaining these transitions is one of the major goals of developmental linguistic theory.

One of these transitions occurs in speech perception. At birth, infants discern differences between all the phonetic units used in the world's languages (Eimas, Miller, and Jusczyk, 1987). All infants show these universal skills, regardless of the language environment in which they are being raised. Data on nonhuman animals' perception of speech suggest that the ability to partition the basic building blocks of speech is deeply rooted in our evolutionary history (Kuhl, 1991a).

When do infants from different cultures begin to diverge? Infants' initial language-universal perceptual abilities are highly constrained just one year later. By the end of the first year, infants fail to discriminate foreign language contrasts they once discriminated (Werker and Tees, 1984), resembling the adult pattern. Adults often find it difficult to perceive differences between sounds not used to distinguish words in their native language. Adult native speakers of Japanese, for example, have great difficulty discriminating American English /r/ and /l/ (Strange, 1995; Best, 1993), and American English listeners have great difficulty hearing the difference between Spanish /b/ and /p/ (Abramson and Lisker, 1970).

Infants' abilities change dramatically over a 6-month period. A recent study completed in Japan shows, for example, that at 6 months Japanese infants respond to the /r-l/ distinction and are as accurate in perceiving it as American 6-month-old infants. By 12 months, Japanese infants no longer demonstrate this ability, even though American infants at that same age have become much better at discriminating the two sounds (Kuhl, Kirtani, et al., 1997).

A similar transition occurs in speech production. Regardless of culture, all infants show a universal progression in the development of speech which encompasses five distinct phases: *Cooing* (1 to 4 months), in which infants produce sounds that resemble vowels; *Canonical Babbling* (5 to 10 months), during which infants produce strings of consonant–vowel syllables, such as "babababa" or "mamamama"; *First Words* (10 to 15 months), wherein infants use a consistent phonetic form to refer to an object; *Two Word Utterances* (18 to 24 months), in which two words are combined in a meaningful way; and *Meaningful Speech* (15 months and beyond), in which infants produce both babbling and meaningful speech to produce long intonated utterances (Ferguson, Menn, and Stoel-Gammon, 1992). Interestingly, deaf infants exposed to a natural sign language, such as American Sign Language (ASL), are purported to follow the same progression using a visual–manual mode of communication (Petitto, 1993).

While infants across cultures begin life producing a universal set of utterances that cannot be distinguished, their utterances soon begin to diverge, reflecting the influence of the ambient language. By the end of the first year, the utterances of infants reared in different countries begin to be separable; infants show distinct patterns of speech production, both in the prosodic (intonational patterns) and phonetic aspects of language, that are unique to the culture in which they are being raised (de Boysson-Bardies, 1993). In adulthood, the distinctive speech motor patterns initially learned contribute to "accents" in speaking another language (Flege, 1988).

The transition in speech perception and production from a pattern that is initially universal across languages to one that is highly specific to a particular language presents one of the most intriguing problems in language acquisition: What causes the transition? We know it is not simply maturational change. In the absence of natural language input, as in the case of socially isolated children (Fromkin et al., 1974; Curtiss, 1977) or cases in which abandoned children were raised quite literally in the wild (Lane, 1976), full-blown linguistic skills do not develop. Linguistic input and social interaction provided early in life appear to be necessary.

The thesis developed here, using the phonetic level, is that linguistic experience produces a special kind of developmental change. Language input alters the brain's processing of the signal, resulting in the creation of complex mental maps. The mapping "warps" underlying dimensions, altering perception in a way that highlights distinctive categories. This mapping is not like traditional psychological learning. In the psychological literature, for example, this kind of learning depends on the presence of specific contingencies that reward certain responses, feedback about the correctness of the response, and step-by-step shaping of the response (Skinner, 1957). The kind of learning reflected in language is very different. While it depends on external information from the environment (language input), it requires neither explicit teaching nor reinforcement contingencies. Given exposure to language in a normal and socially interactive environment, language learning occurs; and the knowledge gained about a specific language is long-lasting and difficult to undo.

Language experience alters perception

The thesis developed here for the phonetic level of language is that ambient language experience produces a "mapping" that alters perception. A research finding that helps explain how this occurs is called the "perceptual magnet effect." It is observed when tokens perceived as exceptionally good representatives of a phonetic category (prototypes) are used in tests of speech perception (Kuhl, 1991b). The notion that categories have prototypes stems from cognitive psychology. Findings in that field show that the members of common categories (like the category bird or dog) are not equal: An ostrich is not as representative of the category bird as a robin; a terrier is not as representative of the category dog as a collie. These prototypes, or best instances of categories, are easier to remember, show shorter reaction times when identified, and are often preferred in tests that tap our favorite instances of categories (Rosch, 1977). This literature motivated us to test the concept that phonetic categories had prototypes, or best instances, in the early 1980s.

Our results demonstrated that phonetic prototypes did exist (Grieser and Kuhl, 1989; Kuhl, 1991b), that they differed in speakers of different languages (Kuhl, 1992; Näätänen et al., 1997; Willerman and Kuhl, 1996), and that phonetic prototypes function like perceptual magnets for other sounds in the category (Kuhl, 1991b). When listeners hear a phonetic prototype and attempt to discriminate it from sounds that surround it in acoustic space, the prototype displays an attractor effect on the surrounding sounds (figure 8.2). It perceptually pulls other members of the category toward it, making it difficult to hear differences between the prototype and surrounding stimuli. Poor instances from the category (nonprototypes) do not function in this way. A variety of experimental tasks produced this result with both consonants and vowels (Iverson and Kuhl, 1995, 1996; Sussman and Lauckner-Morano, 1995). Other studies confirm listeners' skills in identifying phonetic prototypes and show that they are language specific (Kuhl, 1992; Miller, 1994; Willerman and Kuhl, 1996).

Developmental tests revealed that the perceptual magnet effect was exhibited by 6-month-old infants for the sounds of their native language (Kuhl, 1991b). In later studies, cross-language experiments suggest that the magnet effect is the product of linguistic experience (Kuhl et al., 1992). In the cross-language experiment, infants in the United States and Sweden were tested. The infants from both countries were tested with two vowel prototypes, an American English vowel prototype, /i/ (as in "peep"), and a Swedish vowel prototype, /y/ (as in "fye"). The results demonstrated that the perceptual magnet effect in 6-month-old infants was influenced by exposure to a particular language. American infants demonstrated the magnet effect only for the American English /i/; they treated the Swedish /y/ as a nonprototype. Swedish infants showed the opposite pattern, demonstrating the magnet effect for the Swedish /y/ and treating the American English /i/ as a nonprototype. This is the youngest age at which language experience has been shown to affect phonetic perception.

The perceptual magnet effect thus occurs prior to word learning. What this means is that in the absence of formal language understanding or use—before infants utter or understand their first words—infants' perceptual systems strongly conform to the characteristics of the ambient language. We previously believed that word learning caused infants to recognize that phonetic changes they could hear, such as the change that Japanese infants perceived between /r/ and /l/, did not change the meaning of a word in their language. This discovery was thought to cause the change in phonetic perception. We now know that just the opposite is true. Language input sculpts the brain to create a perceptual system that highlights the contrasts used in the language, while de-emphasizing those that do not, and this happens prior to word learning. The change in phonetic perception thus assists word learning, rather than the reverse.

Further tests on adults suggested that the magnet effect distorted perception to highlight sound contrasts in the native language. Studies on the perception of the phonetic units /r/ and /l/, as in the words "rake" and "lake," illustrate this point. The /r-l/ distinction is one notoriously difficult for Japanese speakers, and our studies sought to determine how adults from different cultures perceive these two sounds. To conduct the study, we used computer-synthesized syllables beginning with /r/ and /l/, spacing them at equal physical intervals in a two-dimensional acoustic grid (Iverson and Kuhl, 1996) (figure 8.3A). American listeners identified each syllable as beginning with either /r/ or /l/, rated its category goodness, and estimated the perceived similarity for all possible pairs of stimuli using a scale from "1" (very dissimilar) to "7" (very similar). Similarity ratings were scaled using multidimensional scaling (MDS) techniques. The results provide a map that indicates perceived distance between stimuli. The results revealed that perception distorts physical space. The physical

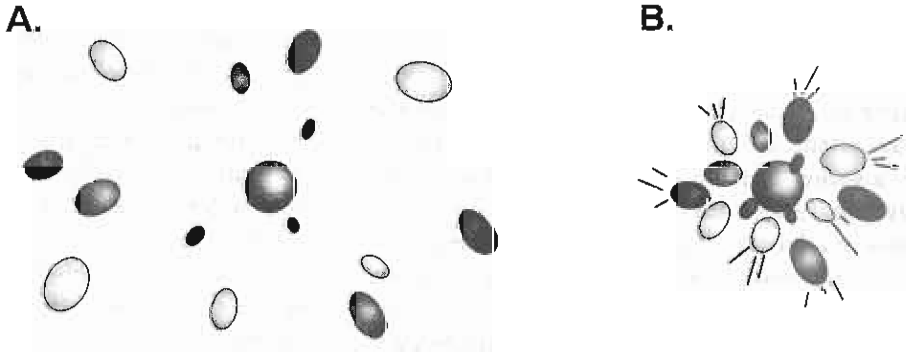

FIGURE 8.2 The perceptual magnet effect. When a variety of sounds in a category surround the category prototype (A), they are perceptually drawn toward the prototype (B). The prototype appears to function like a magnet for other stimuli in the category.

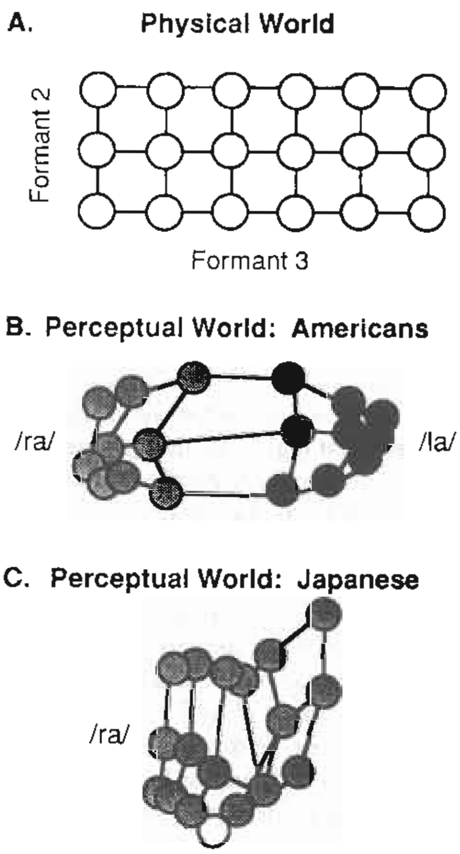

FIGURE 8.3 Physical (acoustic) versus perceptual distance. Consonant tokens of /r/ and /l/ were generated to be equally distant from one another in acoustic space (A). However, American listeners perceive perceptual space as shrunken near the best instances of /r/ (gray dots) and /l/ (black dots) and stretched at the boundary between the two (B). Japanese listeners' perceptual world differs dramatically; neither magnet effects nor a boundary between the two categories are seen (C).

(acoustic) differences between pairs of stimuli were equal; however, perceived distance was "warped" (figure 8.3B). The perceptual space around the best /r/ and the best /l/ was greatly reduced for American listeners, as predicted by the perceptual magnet effect, while the space near the boundary between the two categories was expanded.

This experiment has now been done using Japanese monolingual listeners (Kuhl et al., submitted) and the results show a strong contrast in the way the /r-l/ stimuli are perceived by American and Japanese adults (figure 8.3C). Japanese adults hear almost all the sounds as /r/; there is no /l/ in Japanese. More striking is the complete absence of these magnet and boundary effects in the Japanese MDS solution. The results suggest that linguistic experience forms perceptual maps specifying the perceived distances between speech stimuli, and that these maps differ greatly in people of different cultures.

The critical point for theory is that neither group perceives physical reality, the actual physical differences between sounds. For each language group, experience has altered perception to create a language-specific map of auditory similarities and differences. The map highlights sound contrasts of the speaker's native language by increasing internal category cohesion and maximizing the difference between categories.

The theoretical position developed here is that speech maps are developed early in infancy, prior to the development of word acquisition. The mapping of phonetic information is seen as enabling infants to recognize word candidates. For example, our work shows that Japanese infants fail to discriminate American English /r/ from /l/ at 12 months of age, though they did so perfectly well at 6 months of age (Kuhl, Andruski, et al., 1997). This would assist Japanese infants in word recognition by collapsing /r/- and /l/-like sounds into a single category, making it possible for Japanese infants to perceive their parents' productions of these sounds as one entity at 12 months, when the process of word acquisition begins. If they did not do so, it would presumably make it more difficult to map sound patterns onto objects and events. Mental maps for speech are the front end of the language mechanism. They point infants in the direction needed to focus on the aspects of the acoustic signal that will separate categories in their own native language. They provide a kind of attentional network that may function as a highly tuned filter for language. Such a network would promote semantic and syntactic analysis.

The view that phonetic mapping supports the recognition of higher order units is supported by data showing that slightly later in development infants use information about phonetic units to recognize word-like forms. Work by Jusczyk and his colleagues shows that just prior to word learning, infants prefer word forms that are typical of the native language, ones in which the stress patterns and phoneme combinations conform to the native-language pattern (Jusczyk et al., 1993). At about this age, infants have also been shown capable of learning the statistical probabilities of sound combinations contained in artificial words (Saffran, Aslin, and Newport, 1996). Infants' mapping at the phonetic level is thus seen as assisting infants in chunking the sound stream into higher order units, suggesting that "learning" promotes "development."

The form of learning we are describing is different from historical versions of learning described by psychologists. It does not involve external reinforcement and contingency learning, as in Skinner. It is automatic and unconscious. During the first year of life, infants come to recognize the recurring properties of their native language and mentally store those properties in some form. Uncovering the underlying neural mechanisms that control this kind of learning may aid our general understanding of the kind of learning that makes us unique as a species.

A theory of speech development

Given these findings, how do we reconceptualize infants' innate predispositions as preparing them for experience? One view can be summarized as a three-step model of speech development, called the Native Language Magnet (NLM) model (Kuhl, 1994, 1998a). NLM describes infants' initial state as well as changes brought about by experience with language (figure 8.4). The model demonstrates how infants' developing native-language speech representations might alter both speech perception and production. The same principles apply to both vowel and consonant perception, and the example developed here is for vowels.

Phase 1 describes infants' initial abilities. At birth, infants discriminate the phonetic distinctions of all languages of the world. This is illustrated by a hypothetical F1/F2 coordinate vowel space partitioned into categories (figure 8.4A). These divisions separate perceptually the vowels of all languages. According to NLM, infants' abilities to hear all the relevant differences at this stage do not depend on specific language experience. Infants discriminate language sounds they have never heard.

The boundaries shown in phase 1 initially structure perception in a phonetically relevant way. However, these predispositions seen in humans at birth are not likely to be due to a "language module." This notion is buttressed by the fact that nonhuman animals also show this phenomenon, displaying abilities that were once thought to be exclusively human (Kuhl and Miller, 1975, 1978; Kuhl, 1991a; see also Kluender, Diehl, and Killeen, 1987, and Dooling, Best, and Brown, 1995, for demonstrations of speech perception abilities in nonhumans). This has been interpreted as evidence that the evolution of speech capitalized on sound distinctions well separated by the auditory system (Kuhl, 1989, 1991a).

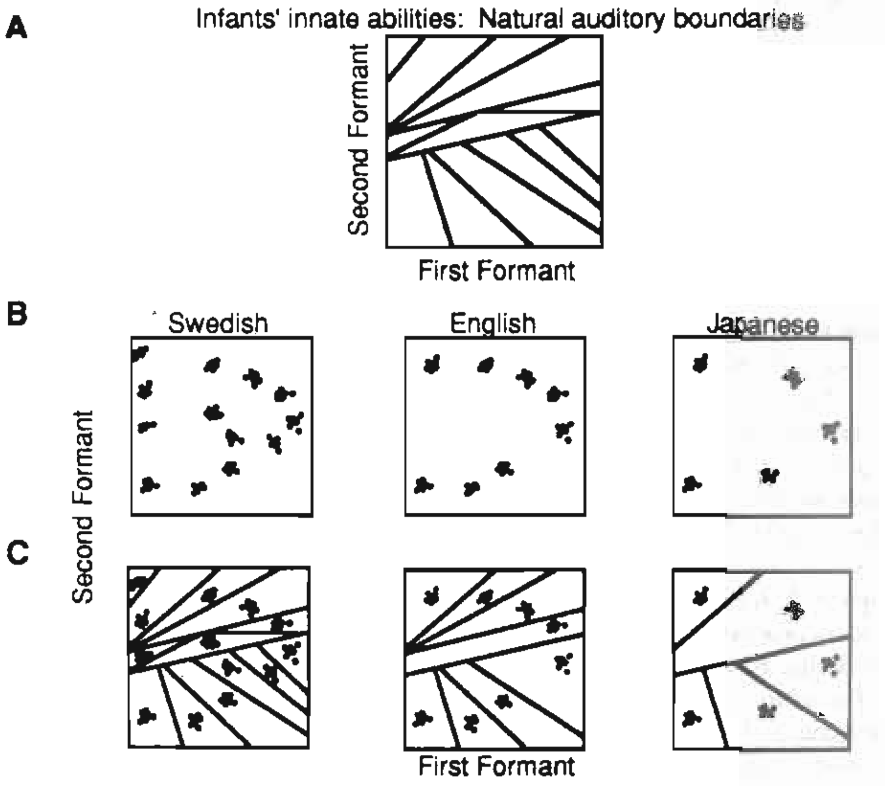

FIGURE 8.4 The native language magnet (NLM) model. (A) At birth, infants perceptually partition the acoustic space underlying phonetic distinctions in a language-universal way. They are capable of discriminating all phonetically relevant differences in the world's languages. (B) By 6 months of age, infants reared in different linguistic environments show an effect of language experience. Infants store incoming vowel information in memory in some form. The resulting representations (shown by the dots) are language-specific, and reflect the distributional properties of vowels in the three different languages. (C) After language-specific magnet effects appear, some of the natural boundaries that existed at birth "disappear." Infants now fail to discriminate foreign-language contrasts they once discriminated.

Phase 2 describes the vowel space at 6 months of age for infants reared in three very different language environments, Swedish, English, and Japanese (figure 8.4B). By 6 months of age, infants show more than the ability to perceptually separate all phonetic categories, as shown in phase 1. The distributional properties of vowels heard by infants being raised in Sweden, America, and Japan differ. According to NLM, infants mentally represent this ambient language information (as shown in figure 8.4B), and their mental representations produce language-specific magnet effects. Thus, by 6 months, language-specific perceptual maps have begun to form.

Interesting questions about phase 2 magnet effects are: How much language input does it take to map speech in this way, and is all language heard by the child (including that from a radio or television) effective in producing this kind of learning? In fact, this was the question asked of me by President William J. Clinton at the White House Conference on "Early Learning and the Brain" in April of 1997. My answer was that at present we have no idea how much language input it takes to show these effects. Moreover, we do not know whether language from a disembodied source (TV, radio) would be sufficient to produce it. By 6 months of age, the earliest age for which we have evidence of magnet effects, our estimates suggest that infants have heard thousands of instances of vowels in *en face* communication with their parents (Kuhl, 1994), but that does not tell us what amount is necessary or whether TV is effective. These questions will require a great deal more work, and we have studies underway that will provide some interesting information.

Phase 3 shows how magnet effects recursively alter the initial state of speech perception, and affect the processing of foreign-language stimuli. Magnet effects cause certain perceptual distinctions to be minimized (those near the magnet attractors) while others are maximized (those near the boundaries between two magnets). The consequence is that some of the boundaries that initially divided the space disappear as the perceptual space is reconfigured to incorporate a language's particular magnet placement (figure 8.4C). Magnet effects functionally erase certain boundaries–those relevant to foreign but not native languages. Listeners' auditory systems still process the acoustic differences that separate categories, but their maps indicate that listeners no longer attend to these differences.

In Phase 3, a perceptual space once characterized by basic "auditory cuts"–boundaries that divide all speech categories, and ones demonstrated in nonhuman animals–has been replaced by a dramatically warped space dominated by magnet effects that completely restructure the space. It is at this phase that infants fail to discriminate foreign-language contrasts that were once discriminable. The mapping of incoming speech has altered which stimulus differences infants respond to, producing a language-specific listener for the first time.

A natural question arising from these data is, what would happen to infants exposed to two different languages. The theory predicts that infants will develop magnet effects for the sound categories of both languages. Interestingly, preliminary data from studies underway suggest that development of two sets of magnet effects is particularly likely when the two languages are spoken by different speakers (mother speaks one language, father speaks another). Presumably, mapping two languages, each spoken by a different speaker, is made easier when infants can separate perceptually the maps for the two languages.

NLM theory offers an explanation for the developmental change observed in speech perception. A developing magnet pulls sounds that were once discriminable toward it, making them less discriminable. Magnet effects should therefore developmentally precede changes in infants' perception of foreign-language contrasts; data indicate that they do (Werker and Polka, 1993). The magnet effect also helps account for the results of studies on the perception of sounds from a foreign language by adults (Best, 1993; Flege, 1993). For example, NLM theory may help explain Japanese listeners' difficulty with American /r/ and /l/. The magnet effect for the Japanese /r/ category prototype (which is neither American /r/ nor /l/) will attract both /r/ and /l/, making the two sounds difficult for native-speaking Japanese people to discriminate (Kuhl et al., submitted). NLM theory argues that early experience establishes a complex perceptual network through which language passes. On this view, one's primary language, and the map that results from early experience, will determine how other languages are perceived.

From a neuroscience perspective, it is of interest to ask whether the developmental change seen in infants' perception of speech is *selective* or *instructive*. Neuroscientists are tempted to relate the finding that synaptic connections are overproduced and then pruned to the developmental time course seen in infants listening to speech, arguing that experience results in selection. But the comparison may not capture the essence of the process. If infants' initial abilities, shared by animals, are simply due to general auditory perceptual mechanisms, while their eventual failures to discriminate are due to the attentional filters produced by magnet effects, what we have to explain physiologically is how the neural system codes these mental maps. The maps would appear to require instruction–some new neural entity sculpted by experience. Could the development of mental maps be accounted for by physiological processes we now understand, such as synaptic pruning, or is something else needed? These questions will undoubtedly keep us busy for some time.

Reinterpreting "critical periods"

The interaction between genetic programming and environmental stimulation is nowhere more evident than in the literature on critical periods in learning (Thorpe, 1961; Marler, 1970). Critical periods are no longer viewed as strictly timed developmental processes with rigid cut-off periods that restrict learning to a specific time frame. Recent studies showing that learning can be stretched by a variety of factors have caused a shift in the terminology used to refer to this period. It is now understood that during "sensitive periods" exposure to specific kinds of information may be more effective than at other times, but that a variety of factors can alter the period of learning. Knudsen's work, for example, on the sound-localization system in the barn owl, shows that the sensitive period for learning the auditory-visual map in the optic tectum can be altered by a variety of factors that either shorten or extend the learning period; the learning period closes much earlier, for instance, if experience occurs in a more natural environment (Knudsen and Knudsen, 1990; Knudsen and Brainerd, 1995).

The idea that sensitive periods define "windows of opportunity" for learning, during which environmental stimulation is highly effective in producing developmental change, remains well supported both in the human and the animal literature. The ability to learn is not equivalent over time. The question is: What causes a decline in the ability to learn over the life span?

The sensitive period denotes a process of learning that is constrained primarily by time, or factors such as hormones, that are outside the learning process itself. There is an alternative possibility suggested by the studies on speech: Later learning may be limited by the fact that learning itself alters the brain, and the brain's resulting structure may produce a kind of interference effect that impacts later learning. For instance, if NLM's argument that learning involves the creation of mental maps for speech is true, this would mean that learning "commits" neural structure in some way. According to the model, speech processing is affected by this neural structure, and future learning is as well. The mechanisms governing an organism's general ability to learn may not have changed. Rather, initial learning may result in a structure that reflects environmental input and, once committed, the learned structure may interfere with the processing of information that does not conform to the learned pattern. On this account, initial learning can alter future learning independent of a strictly timed period.

On this *interference* account, brain "plasticity" (ability to change) would be governed from a statistical standpoint. When additional input does not cause the overall statistical distribution to change substantially, the organism becomes less sensitive to input. Hypothetically, for instance, the infant's representation of the vowel /a/ might not change when the millionth token of the vowel /a/ is heard. Plasticity might thus be independent of time, but dependent on the amount and variability provided by experience. At some time in the life of an organism, one could conceive of a point beyond which new input no longer alters the underlying distribution, and this could, at least in principle, reduce the system's plasticity.

The interference view may account for some aspects of second language learning. When acquiring a second language, certain phonetic distinctions are notoriously difficult to master both in speech perception and production. Take the case of the /r-l/ distinction for native speakers of Japanese. Both hearing the distinction and producing it are very difficult for native speakers of Japanese (Goto, 1971; Miyawaki et al., 1975; Yamada and Tohkura, 1992). According to NLM, this is because exposure to Japanese early in life altered the Japanese infant's perceptual system, resulting in magnet effects for the Japanese phoneme /r/, but not for the American English /r/ or /l/. Once in place, Japanese magnet effects would not make it easy to process American English. American English /r/ and /l/ would be assimilated to Japanese /r/ (Kuhl et al., submitted).

A second language learned later in life (after puberty) may require separation between the two systems to avoid interference. Data gathered using fMRI techniques indicate that adult bilinguals who learned both languages early in life activate overlapping regions of the brain when processing the two languages, while those who learned the second language later activate two distinct regions of the brain for the two languages (Kim et al., 1997). This is consistent with the idea that the brain's processing of a primary language can interfere with the second language. This problem is avoided if both are learned early in development.

The general thesis is that acquiring new phonetic categories as adults is difficult because the brain's mental maps for speech, formed on the basis of the primary language, are incompatible with those required for the new language; hence, interference results. Early in life, interference effects are minimal and new categories can be acquired because input continues to revise the statistical distribution. As mentioned earlier, limited evidence suggests that infants exposed to two languages do much better if each parent speaks one of the two languages than when both parents speak both languages. This may be because it is easier to map two different sets of phonetic categories (one for each of the two languages) if there is some way to keep them perceptually separate. Males and females produce speech in different frequency ranges, and this could make it easier to maintain separation.

These two factors–a maturationally defined temporal window governed by genetic factors, and the neural commitment that results from initial learning–could both be operating to produce constraints on learning a second language later in life. If a maturational process induces neural readiness at a particular time, input that misses this timing could reduce learning. At the same time, an interference factor produced by mapping language input might provide an independent mechanism that contributes to the difficulty in readily learning a second language in adulthood.

Vocal learning

Vocal learning–an organism's dependence on auditory input both from itself and others to acquire a vocal repertoire–is not common among mammals, but is exhibited strikingly in songbirds (Marler 1990; Konishi, 1989). In certain songbirds, and in humans, young members of the species not only learn the perceptual properties of their conspecific communicative signals, but also become proficient producers of those signals. A great deal of research on birds (see Doupe, 1998, for review) and infants (Stoel-Gammon and Otomo, 1986; Oller et al., 1976) has shown that hearing the vocalizations of others, and hearing oneself produce sound, are both essential to the development of vocalizations. Deaf infants, for example, do not babble normally (Oller and MacNeilage, 1983), nor do deafened birds (Konishi, 1965; Nottebohm, 1967). And infants tracheotomized at the time at which they would normally be babbling also results in abnormal patterns of development that persist (Locke and Pearson, 1990).

In the case of humans, speech motor patterns learned at the appropriate time become difficult to alter later in life. Speakers who learn a second language after puberty, for example, produce it with an accent typical of their primary language (Flege, 1993). Most speakers of a second language would like to speak like a native speaker, without an accent, but this is difficult to do, even with long-term instruction.

When do we adopt the indelible speech patterns that will mark us as native speakers of a particular language for our entire lives? Developmental studies suggest that by one year of age language-specific patterns of speech production appear in infants' spontaneous utterances (de Boysson-Bardies, 1993; Vihman and de Boysson-Bardies, 1994). However, the fundamental capacity to reproduce the sound patterns one hears is in place much earlier. In a recent study, Kuhl and Meltzoff (1996) recorded infant utterances at 12, 16, and 20 weeks of age while the infants watched and listened to a video recording of a woman producing a vowel, /a/, /i/, or /u/. Infants watched the video for 5 minutes on each of three consecutive days. The results showed a developmental change in infants' vowel productions between 12 and 20 weeks of age. The areas of vowel space occupied by infants' /a/, /i/, and /u/ vowels become progressively more tightly clustered at each age, and by 20 weeks, a "vowel triangle" typical of that produced in every language of the world, had emerged in the infants' own region of the vowel space (figure 8.5). This demonstrated that between 12 and 20 weeks of age, infants' sound pro-

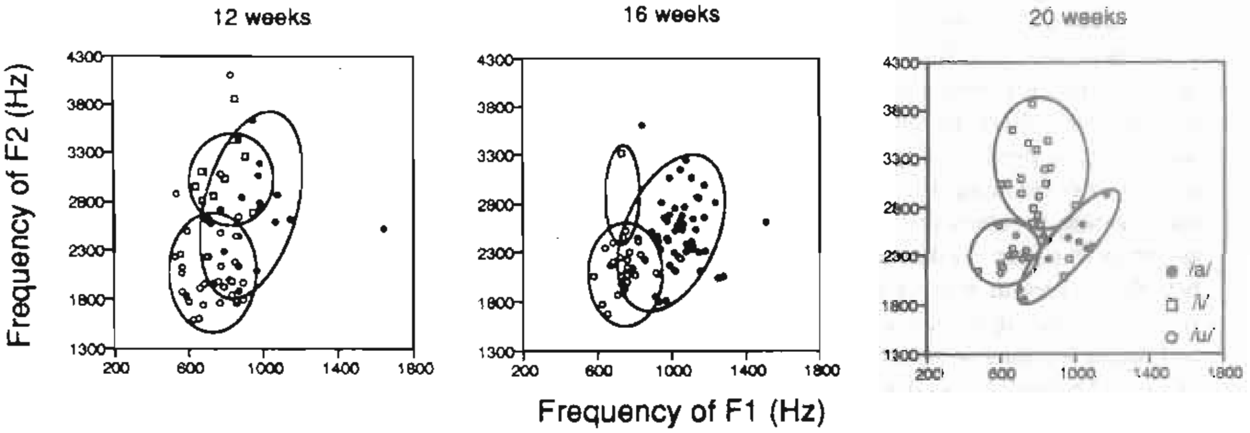

FIGURE 8.5 The location of /a/, /i/, and /u/ vowels produced by 12-, 16-, and 20-week-old infants. Infants' vowel productions show progressively tighter clustering in vowel space over the 8-week period and reflect differences between the three vowel categories seen in adults' productions.

ductions were changing in a way that brought them closer to the adult pattern.

Direct evidence that infants were vocally imitating was also obtained in the study. By 20 weeks, infants were shown to reproduce the vowels they heard. Infants exposed to /a/ were more likely to produce /a/ than when exposed to either /i/ or /u/; similarly, infants exposed to either /i/ or /u/ were more likely to produce the vowel in that condition than when listening to either of the two alternate vowels. The total amount of exposure to a specific vowel in the laboratory was just 15 minutes; yet this was sufficient to influence infants' productions. If 15 minutes of laboratory exposure to a vowel is sufficient to influence infants' vocalizations, then listening to ambient language for weeks would be expected to provide a powerful influence on infants' production of speech. These data suggest that infants' stored representations of speech not only alter infant perception, but alter production as well, serving as auditory patterns that guide motor production. Stored representations are thus viewed as the common cause for both the tighter clustering observed in infant vowel production and the tighter clustering observed in infant vowel perception (figure 8.6).

This pattern of learning and self-organization, in which perceptual patterns stored in memory serve as guides for production, is strikingly similar for birdsong and speech (Doupe and Kuhl, 1999), in visual-motor learning in which such nonspeech oral movements as tongue protrusion and mouth opening are imitated (Meltzoff and Moore, 1977, 1994), and in language involving both sign (Petitto and Marentette, 1991) and speech (Kuhl and Meltzoff, 1996). In each of these cases, perceptual experience establishes a representation that guides sensorimotor learning. In the case of infants and speech, perception affects production in the earliest stages of language learning, reinforcing the idea that the speech motor patterns of a specific language are formed very early in life. Once learned, motor patterns may also further development by altering the probability that infants will acquire words that contain items they are capable of producing.

The role of vision in speech perception

The link between perception and production can be seen in another experimental situation in speech, and there is some suggestion that this is mirrored in birdsong learning. Speech perception in adults is strongly affected by the sight of a talker's mouth movements during speech, indicating that our representational codes for speech contain both auditory and visual information. One of the most compelling examples of the polymodal nature of speech representations is auditory-visual illusions that result when discrepant information is sent to two separate modalities. One such illusion occurs when auditory information for /b/ is combined with visual information for /g/ (McGurk and MacDonald, 1976; Green et al., 1991; Kuhl et al., 1994; Massaro, 1987). Perceivers report the phenomenal

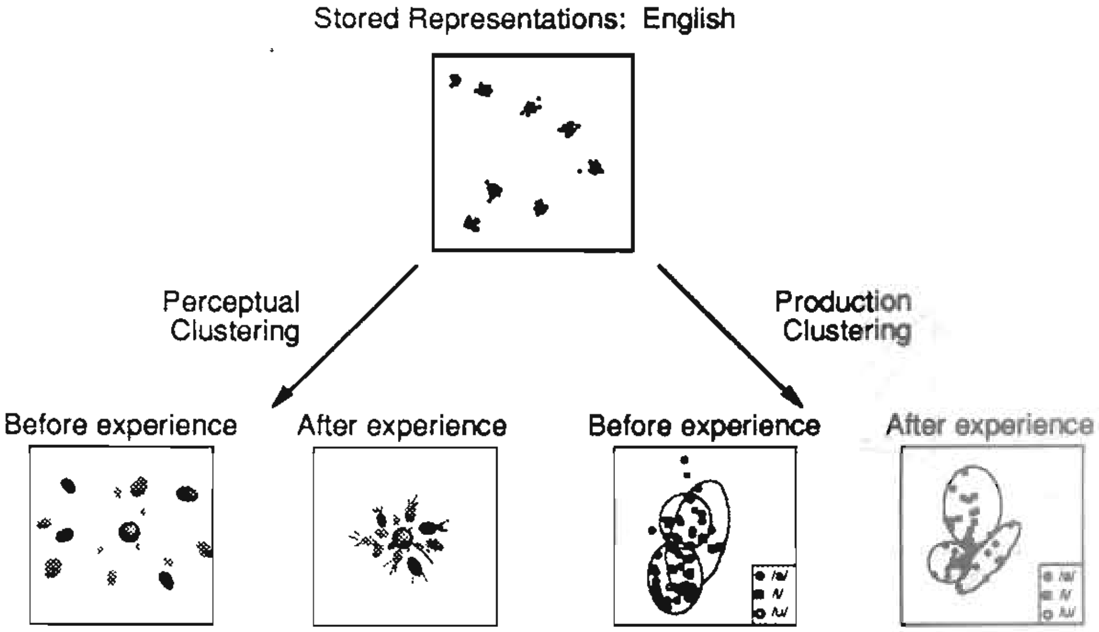

FIGURE 8.6 Stored representations of native-language speech affect both speech perception, producing the perceptual clustering evidenced by the magnet effect, as well as speech production, producing the increased clustering seen in infants' vocalizations over time.

impression of an intermediate articulation (/da/ or /tha/) despite the fact that this information was not delivered by or to either sense modality. This is a very robust phenomenon and is readily obtained even when the information from the two modalities comes from different speakers, such as when a male voice is combined with a female face (Green et al., 1991). In this case, there is no doubt that the auditory and visual signals do not belong together. Yet the illusion is still unavoidable–our perceptual systems combine the multimodal information (auditory and visual) to give a unified percept.

Young infants are also affected by visual information. Infants just 18–20 weeks old recognize auditory-visual correspondences for speech, akin to what adults do when lipreading. In these studies, infants looked longer at a matching face–one pronouncing a vowel that matched the vowel sound they heard–than at a mismatched face (Kuhl and Meltzoff, 1982). Young infants demonstrate knowledge about both the auditory and visual information contained in speech, supporting the notion that infants' stored speech representations contain information of both kinds. Additional demonstrations of auditory-visual speech perception in infants suggest that there is a left-hemisphere involvement in the process (MacKain et al., 1983), and more recent data by Rosenblum, Schmuckler, and Johnson (1997) and Walton and Bower (1993) suggest that the ability to match auditory and visual speech is present in newborns.

Visual information thus plays a very strong role in speech perception. When listeners watch the face of the talker, studies show that perception of the message is greatly enhanced, in effect contributing the equivalent of a 20-dB boost (quite substantial) in the signal. This supports the view that speech in humans is polymodally represented, and that this is the case very early in development.

Nature of language input to the child

Research supports the idea that caretakers around the world use a near-universal speaking style when addressing infants and that infants prefer it over other complex acoustic signals (Fernald, 1985; Fernald and Kuhl, 1987). Estimates indicate that a typical listening day for a 2-year-old includes 20,000–40,000 words (Chapman et al., 1992). Speech addressed to infants (often called "motherese" or "parentese") is unique: It has a characteristic prosodic structure with a higher pitch, a slower tempo, and exaggerated intonation contours, and it is syntactically and semantically simplified.

In new studies, we have uncovered another modification parents make when addressing infants–one that may be important to infant learning. We examined natural language input at the phonetic level to infants in the United States, Russia, and Sweden (Kuhl, Andruski, et al., 1997). The study shows that across three very diverse languages, infant-directed speech exhibited a universal alteration of phonetic units when compared to adult-directed speech. Parents addressing their infants produced acoustically more extreme tokens of vowel sounds, resulting in a "stretching" of the acoustic space encompassing the vowel triangle (figure 8.7). A stretched vowel triangle not only makes speech more discriminable for infants, it also highlights critical spectral parameters that allow speech to be produced by the child. The results suggest that at

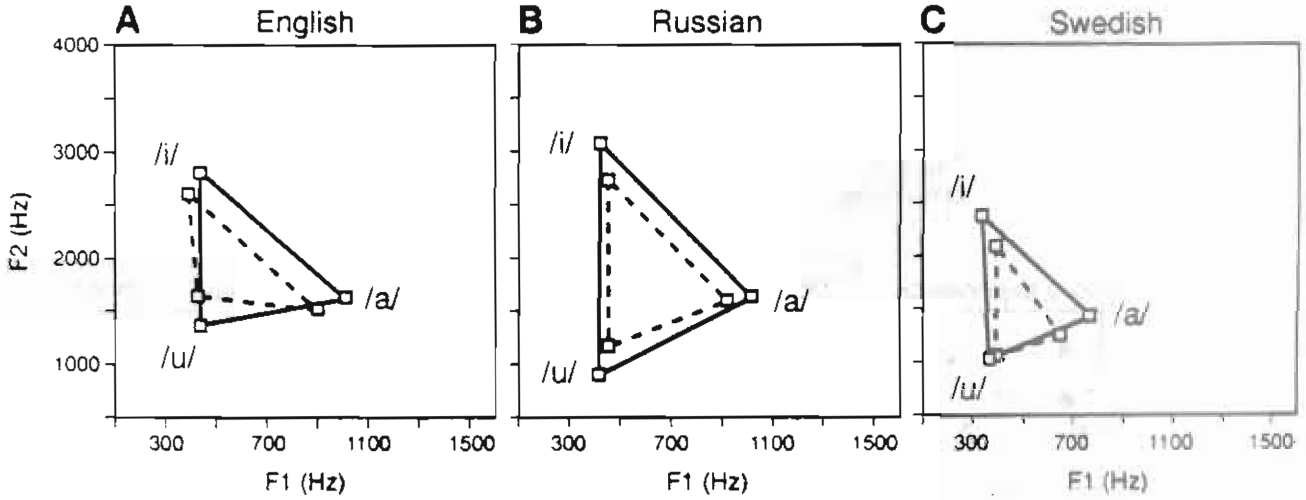

FIGURE 8.7 The vowel triangle of maternal speech directed toward infants (solid line) across three diverse languages shows a "stretching" relative to the adult-directed vowel triangle (dashed line), an effect that both makes vowels more discriminable and highlights the abstract features that infants must use to produce speech themselves.

the phonetic level of language, linguistic input to infants provides exceptionally well-specified information about the units that form the building blocks for words.

Thus, when adults speak to normally developing infants, they enhance phonetic distinctions. In recent studies, language-delayed children showed substantial improvements in measures of speech and language after treatment in a program in which they listened to speech altered by computer to exaggerate phonetic differences (Merzenich et al., 1996; Tallal et al., 1996). This kind of speech may aid infants' discovery of the dimensions of sound that they need to attend to in order to process speech efficiently. In the study, mothers' vowels in speech to children were what acousticians call "hyperarticulated" (Lindblom, 1990), ones that are perceived by adults as better instances of vowel categories (Iverson and Kuhl, 1995; Johnson, Flemming, and Wright, 1993). Parental speech thus contains more prototypical instances, and as shown in the work reviewed previously, these are the very kinds of sounds that produce the perceptual magnet effect. Language input to infants may therefore provide an ideal signal for constructing perceptual maps.

Brain correlates

Since the classic reports of Broca and Wernicke on patients with language deficits typical of aphasia, we have known that the two hemispheres are not equal in the extent to which they subserve language. In the 1960s, behavioral studies on language processing in normal adults contributed additional evidence of the left-hemisphere specialization for language, showing a dissociation for processing speech (left hemisphere) and nonspeech (right hemisphere) signals (Kimura, 1961).

Studies of the brain's organization of language have appeared in increasing numbers with the advent of modern neuroimaging techniques such as PET, positron emission tomography (Peterson et al., 1990; Posner et al., 1988); fMRI, functional magnetic resonance imaging, (Neville et al., 1998); ERP, event-related potentials (Neville, Mills, and Lawson, 1992; Osterhout and Holcomb, 1992); and MEG, magnetoencephalography (Näätänen et al., 1997). While this field is still emergent, there are some conclusions that take us beyond what early studies have shown regarding language and the brain. The new studies suggest, for example, that there is not one unified "language area" in the brain where linguistic signals are processed. Different brain systems subserve different aspects of language processing, and the language processing areas of the brain include many more regions than the classic Broca's and Wernicke's areas.

The imaging studies confirm a dissociation for processing speech and nonspeech signals found in earlier behavioral studies. One study (Zatorre et al., 1992) used PET scans to examine phonetic as opposed to pitch processing. Subjects in the study had to judge the final consonant of the syllable in the phonetic task and the pitch of the syllable (high or low) in the pitch task. The results showed that phonetic processing engaged the LH while pitch processing engaged the RH. This dissociation between the phonetic and nonphonetic processing of auditory dimensions is mirrored in studies using vowels at different pitches and MEG (Poeppel et al., 1997).

Given these results, an important question from the standpoint of development is when the left hemisphere becomes dominant in the processing of linguistic information. Lenneberg (1967) hypothesized that the two hemispheres are equipotential for language until approximately two years of age, at which time LH dominance begins to develop and continues until puberty. However, this theory is contradicted by data suggesting that children with LH versus RH damage at an early age displayed different deficits in language abilities: Early LH damage affects language abilities more than early RH damage (Witelson, 1987).

Behavioral studies have established the right-ear advantage (REA) for speech for verbal stimuli and the left-ear advantage (LEA) for musical and environmental sounds using the dichotic listening task in children as young as 2.5 years (Bever, 1971; Kimura, 1963). But what of infants? Glanville, Best, and Levenson (1977) reported an REA for speech contrasts and an LEA for musical sounds using a cardiac orienting procedure in 3-month-olds. Only two studies provide data on infants' differential responses to speech and music at ages younger than 2 months. In one study, infants' discriminative capacities for speech and music were examined in 2-, 3-, and 4-month-old infants using a cardiac-orienting procedure. The results demonstrated an REA for speech discrimination in 3-month and 4-month-old infants, but not in 2-month-old infants. In addition, an LEA was shown for musical-note discrimination at all three ages. Finally, tests on 2-month-olds conducted by Vargha-Khadem and Corballis (1979) showed infants discriminated speech contrasts equally with both hemispheres. In other words, the results suggest that speech may not be lateralized in 2-month-old infants, but becomes so by 4 months of age.

This issue of the onset of laterality and the extent to which it depends on linguistic experience may be resolved with future research using techniques that can be used throughout the life span. One such technique is the mismatched negativity (MMN), a component of the auditorially evoked event-related potential (ERP). The MMN is automatically elicited by a discriminable change in a repetitive sound pattern and its generation appears to represent the detection of a change in the neural sensory-memory representation established by the repeated stimulus (see Näätänen, 1990, 1992, for review). MMNs to a change in a speech stimulus have been well documented in adult listeners (e.g., Kraus et al., 1992). The MMN has been established in children (Kraus et al., 1993) and most recently in infants (Cheour-Luhtanen et al., 1995; Kuhl, 1998b; Pang et al., 1998). In adult ERP studies, a left-hemisphere asymmetry is evident (Pang et al., 1998), but it has not been observed in newborns (Cheour-Luhtanen et al., 1995).

In summary, there is no strong evidence at present that the bias toward left-hemisphere processing for language is present at birth. The data suggest that it may take experience with linguistically patterned information to produce the left-hemisphere specialization. Thus, there is support for a specialization for language in infancy, but one that develops, rather than one that exists at birth. Moreover, the input that is eventually lateralized to the left hemisphere can be either speech or sign, indicating that it is the linguistic/communicative significance of the signals, rather than their specific form, that accounts for the specialization.

Conclusions

Research has shown that in the first year of life infants learn a great deal about the perceptual characteristics of their native language, and this subsequently alters the perception and production of speech. According to the native language magnet model, perceptual learning early in life results in the formation of stored representations that capture native-language regularities. The theory emphasizes the role of linguistic input. Input does not act like a trigger for innately stored information. Rather, it is mapped in such a way as to "warp" the underlying acoustic space. Stored representations act like perceptual magnets for similar patterns of sound, resulting in maps that specify perceived distances between sounds, and create categories. The map shrinks perceptual distances near a category's most typical instances and stretches perceptual distances between categories. Perceptual maps differ in adults who speak different languages and are polymodally mapped, containing auditory, visual, and motor information. The magnet effects and the mental maps they produce help explain how native-language speech develops, as well as the relative inability of adults to readily acquire a foreign language.

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