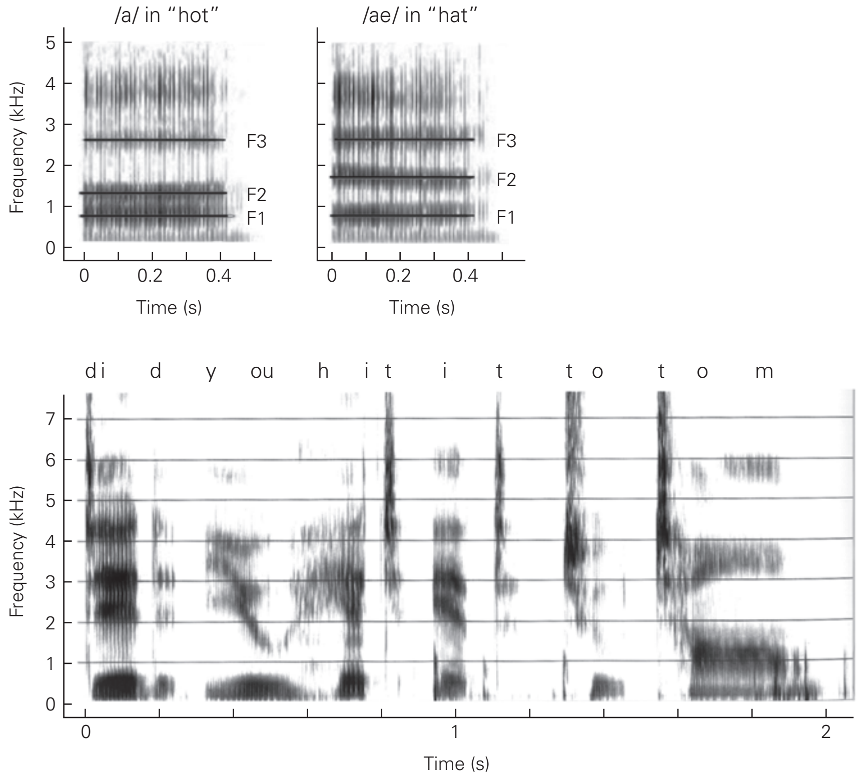


Figure 55–1 Formant frequencies. Formants are systematic variations in the concentration of energy at various sound frequencies and represent resonances of the vocal tract. They are shown here as a function of time in a spectrographic analysis of speech. The formant patterns for two simple vowels (/a/ and /ae/) spoken in isolation are distinguished by differences in formant 2 (F2). Formant patterns for the sentence "Did you hit it to Tom?" spoken slowly and clearly illustrate the rapid changes that underlie normal speech. (Data from Patricia Kuhl.)

to distinguish semantically different sounds and thus understand speech. Whereas in written language, spaces are customarily inserted between words, in speech, there are no acoustic breaks between words. Thus, speech requires a process that can detect words on the basis of something other than sounds bracketed by silence. Computers have a great deal of trouble recognizing words in the normal flow of speech.

Phonotactic rules specify how phonemes can be combined to form words. Both English and Polish use the phonemes /z/ and /b/, for example, but the combination /zb/ is not allowed in English, whereas in Polish, it is common (as in the name *Zbigniew*).

Morphemes are the smallest structural units of a language, best illustrated by prefixes and suffixes. In English, for example, the prefix *un* (meaning *not*) can be added to many adjectives to convey the opposite meaning (eg, *unimportant*). Suffixes often signal the tense or number of a word. For example, in English, we add *s* or *es* to indicate more than one of something (*pot* becomes *pots*, *bug* becomes *bugs*, or box becomes *boxes*). To indicate the tense of a regular verb, we add an ending to the word (eg, *play* can become *plays*, *playing*, and *played*). Irregular verbs do not follow the rule (eg, *go* becomes *went* rather than *goed* and *break* becomes *broke* rather than *breaked*). Every language has a different set of rules for altering the tense and number of a word.

Finally, to create language, words have to be strung together. *Syntax* specifies word and phrase order for a given language. In English, for example, sentences typically conform to a subject-verb-object order (eg, *He eats cake*), whereas in Japanese, it is typically subject-object-verb (eg, *Karewa keeki o tabenzasu*, literally *He cake eats*). Languages have systematic differences in the order of larger elements (noun phrases and verb phrases) of a sentence, and in the order of words within phrases, as illustrated by the difference between English and French noun phrases. In English, adjectives precede the noun (eg, *a very intelligent man*), whereas in French, most follow the noun (eg, *un homme tres intelligent*).

Language Acquisition in Children Follows a Universal Pattern

Regardless of culture, all children initially exhibit universal patterns of speech perception and production that do not depend on the specific language children hear (Figure 55–2). By the end of the first year, infants have learned through exposure to a specific language which phonetic units convey meaning in that language and to recognize likely words, even though they do not yet understand those words. By 12 months of age, infants understand approximately 50 words and have begun to produce speech that resembles the native language. By the age of 3 years, children know approximately 1,000 words (by adulthood 70,000), create long adult-like sentences, and can carry on a conversation. Between 36 and 48 months, children respond to the differences between grammatical and ungrammatical sentences in an adult-like way, although tests using the most complex sentences indicate that the intricacies of grammar are not mastered until late childhood, between 7 and 10 years of age.

In the last half of the 20th century, debate on the nature and acquisition of language was ignited by a highly publicized exchange between a strong learning theorist and a strong nativist. In 1957, the behavioral psychologist B. F. Skinner proposed that language was acquired through learning. In his book *Verbal Behavior*, Skinner argued that language, like all animal behavior, was a learned behavior that developed in children as a function of external reinforcement and careful parental shaping. By Skinner's account, infants learn language as a rat learns to press a bar—through monitoring and management of reward contingencies. The nativist Noam Chomsky, writing a review of *Verbal Behavior*, took a very different position. Chomsky argued that traditional reinforcement learning has little to do with the ability of humans to acquire language. Instead, he proposed that every individual has an innate "language faculty" that includes a universal grammar and a universal phonetics; exposure to a specific language triggers a "selection" process for one language.

More recent studies of language acquisition in infants and children have clearly demonstrated that the kind of learning going on in infancy does not resemble that described by Skinner with its reliance on external shaping and reinforcement. At the same time, a nativist account such as Chomsky's, in which the language the infant hears triggers selection of one of several innate options, also does not capture the process.

The "Universalist" Infant Becomes Linguistically Specialized by Age 1

In the early 1970s, psychologist Peter Eimas showed that infants were especially good at hearing the acoustic changes that distinguish phonetic units in the world's languages. When speech sounds were acoustically varied in small equal steps to form a series ranging from one phonetic unit to another, say from /ba/ to /pa/, Eimas showed that infants could discern very slight acoustic changes at the locations in the series (the "boundary") where adults heard an abrupt change between the two phonetic categories, a phenomenon called *categorical perception.* Eimas demonstrated that infants could detect these slight acoustic changes at the phonetic boundary between two categories for phonetic units in languages they had never experienced, whereas adults have this ability only for phonetic units in languages in which they are fluent. Japanese people, for example, find it very difficult to hear the acoustic differences between the American English /r/ and /l/ sounds. Both are perceived as Japanese /r/, and as we have seen, Japanese speakers use the two sounds interchangeably when producing words.

Categorical perception was originally thought to occur only in humans, but in 1975, cognitive neuroscientists showed that it exists in nonhuman mammals such as chinchillas and monkeys. Since then, many studies have confirmed this result (as well as identifying species differences between mammals and birds). These studies suggest that the evolution of phonetic units was strongly influenced by preexisting auditory structures and capacities. Infants' ability to hear all possible differences in speech prepares them to learn any language; at birth, they are linguistic "universalists."

Speech production develops simultaneously with speech perception (Figure 55–2). All infants, regardless of culture, produce sounds that are universal. Infants "coo" with vowel-like sounds at 3 months of age and "babble" using consonant–vowel combinations at about 7 months of age. Toward the end of the first year, language-specific patterns of speech production begin to emerge in infants' spontaneous utterances. As children approach the age of 2 years, they begin to mimic the sound patterns of their native language. Chinese toddlers' utterances reflect the pitch, rhythm, and phonetic structure of Mandarin, and the utterances of British toddlers sound distinctly British. Infants develop an ability to imitate the sounds they hear others produce as early as 20 weeks of age. Very early in development, infants begin to master the subtle motor patterns required to produce their "mother tongue." Speech-motor patterns acquired in the earliest stages of language learning persist throughout life and influence the sounds, tempo, and rhythm of a second language learned later.

Right before the onset of first words, infants' abilities to discriminate native and nonnative phonetic units show a dramatic shift. At 6 months of age, infants can discriminate all phonetic units used in all languages, but by the end of the first year, they fail to discriminate phonetic changes that they successfully recognized 6 months earlier. At the same time, infants become significantly more adept at hearing native-language phonetic differences. For example, when American

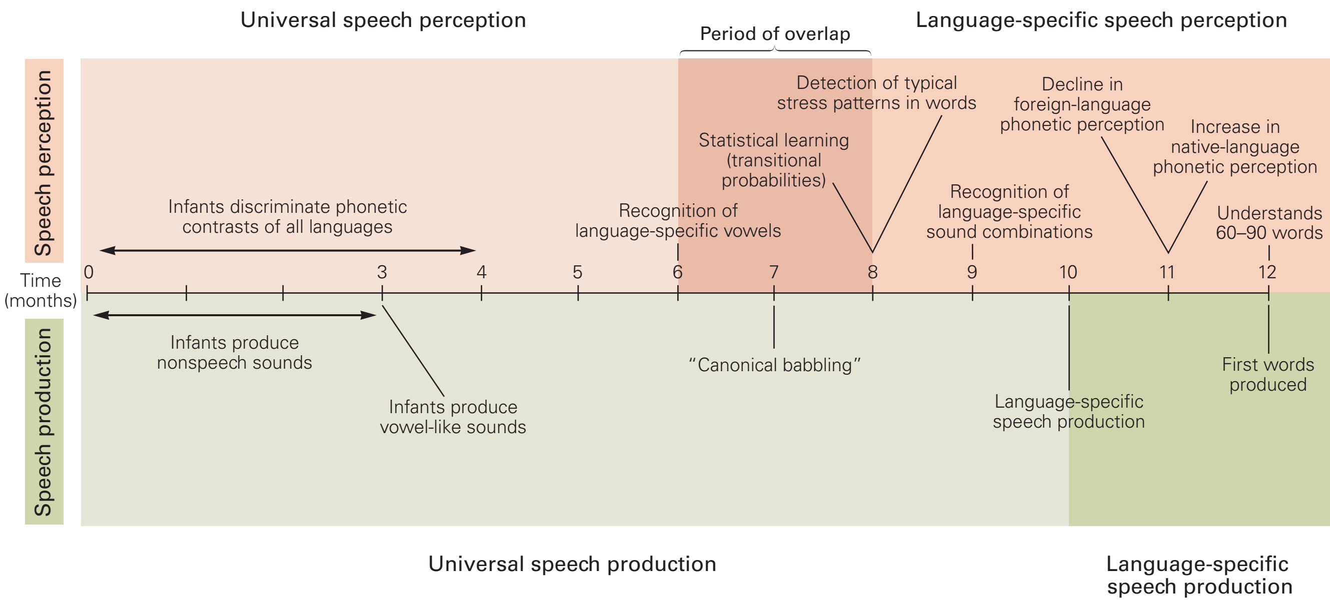


Figure 55–2 Language development progresses through a standard sequence in all children. Speech perception and production in children in various cultures initially follow a language-universal pattern. By the end of the first year of life, language-specific patterns emerge. Speech perception becomes language-specific before speech production. (Adapted, with permission, from Doupe and Kuhl 1999.)

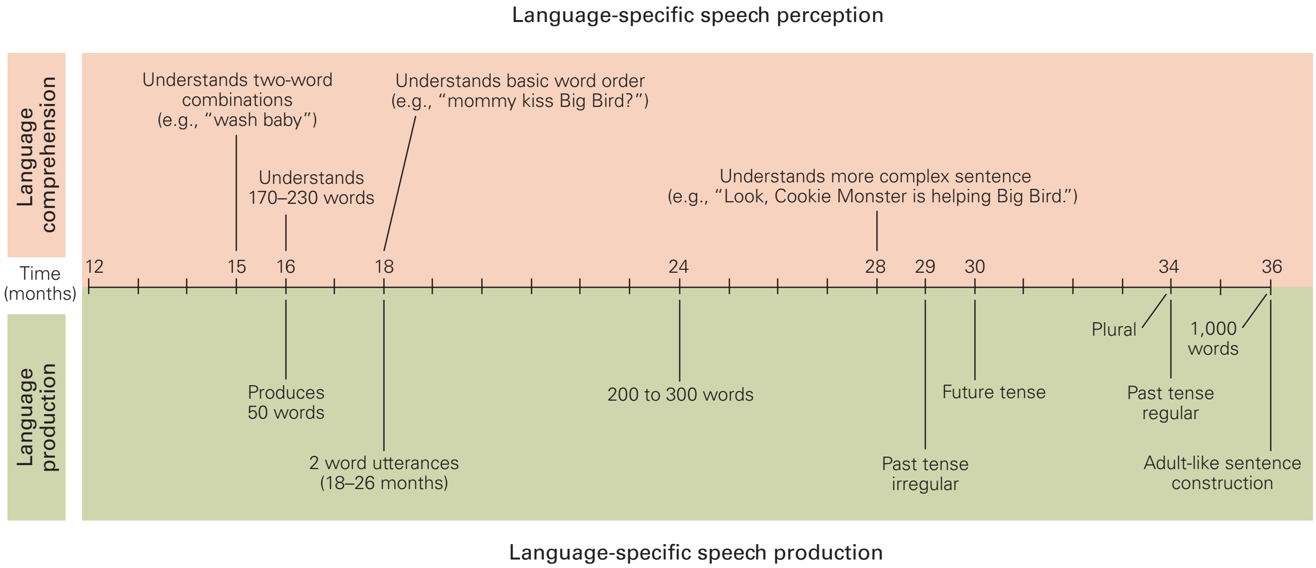
and Japanese infants were tested between 6 and 12 months of age on the discrimination of the American English /r/ and /l/, American infants improved significantly between 8 and 10 months, whereas Japanese infants declined, suggesting that this is a sensitive period for phonetic learning. Moreover, infants' native-language discrimination ability at 7.5 months of age predicts the rate at which known words, sentence complexity, and mean length of utterance grow between 14 and 30 months.

If the second half of the first year is a sensitive period for speech learning, what happens when infants are exposed to a new language during this time? Do they learn? When American infants were exposed to Mandarin Chinese in the laboratory between 9 and 10 months of age, the infants learned if exposure occurred through interaction with a human being; infants exposed to the exact same material through television or audiotape with no live human interaction do not learn (Figure 55–3). When tested, the performance of the group exposed to live speakers was statistically indistinguishable from that of infants raised in Taiwan who had listened to Mandarin for 10 months. These results established that, at 9 months of age, the right kind of exposure to a foreign language permits phonetic learning, supporting the view that this is a sensitive period for such learning. The study also demonstrated, however, that social interaction plays a more significant role in learning than previously thought.

Further work showed that the degree to which infants track the eye movements of the tutor—watching what she is looking at as she names objects in the foreign language—correlates strongly with neural measures of phonetic and word learning after exposure to the new language, again implicating social brain areas in language learning.

An infant's ability to pick up social cues is essential to language learning, but what other skills promote learning during this critical period? Studies suggest that early exposure to speech induces an implicit learning process that increases native-language discrimination and reduces the infant's innate ability to hear distinctions between the phonetic units of all other languages. Infants are sensitive to the statistical properties of the language they hear. Distributional frequency patterns of sounds affect infants' speech learning by 6 months of age. Infants begin to organize speech sounds into categories based on *phonetic prototypes*, the most frequently occurring phonetic units in their language.

Six-month-old infants in the United States and Sweden were tested with prototypical English and Swedish vowels to examine whether infants discriminated acoustic variations in the vowels, like those that occur when different talkers produce them. By 6 months of age, the American and Swedish infants ignored



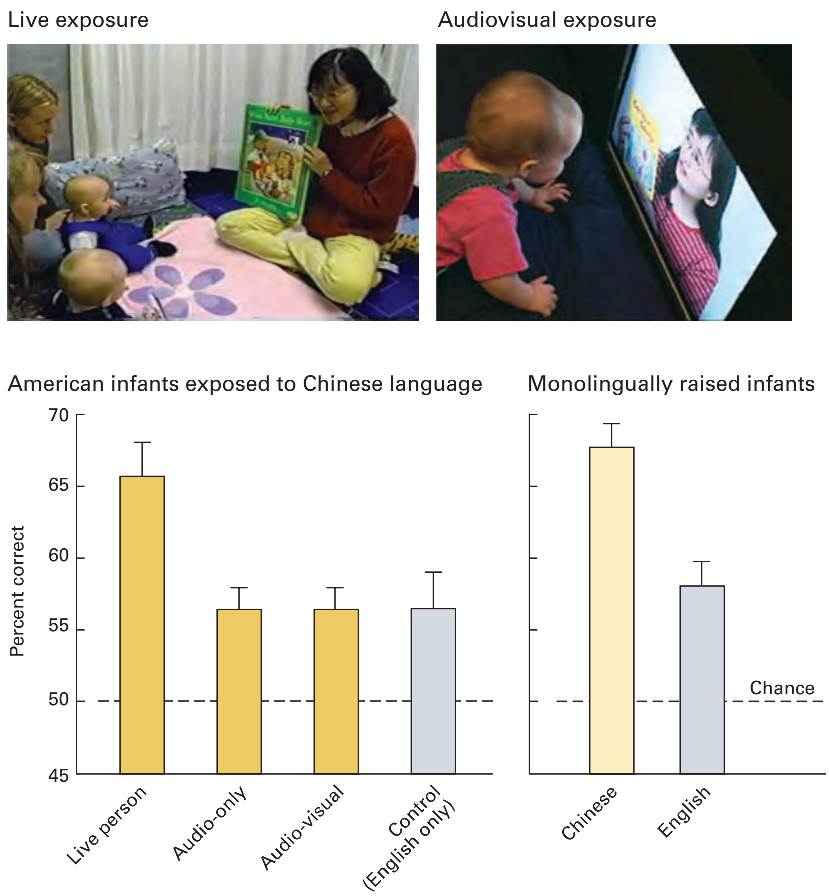


Figure 55–3 Infants can learn the phonemes of a nonnative language at 9 months of age. Three groups of American infants were exposed for the first time to a new language (Mandarin Chinese) in 12 25-minute sessions between the ages of 9 and 10.5 months. One group interacted with live native speakers of Mandarin; a second group was exposed to the identical material through television; and a third group heard tape recordings only. A control group had similar language sessions but heard only English. Performance on discrimination of Mandarin phonemes was tested in all groups after exposure (age 11 months). (Reproduced, with permission, from Kuhl, Tsao, and Liu 2003.)

Left. Only infants exposed to live Mandarin speakers discriminated the Mandarin phonemes. Infants exposed through TV or tapes showed no learning, and their performance was indistinguishable from that of control infants (who heard only English).

Right. The performance of American infants exposed to live Mandarin speakers was equivalent to that of monolingual Taiwanese infants of the same age who had experienced Mandarin from birth.

acoustic variations around native language prototypes but not with nonnative prototypes. Paul Iverson has shown that language experience alters the acoustic features to which speakers of different languages attend and distorts perception around category prototypes. This makes stimuli perceptually more similar to the prototype, which helps explain why 11-month-old Japanese infants fail to discriminate English /r/ and /1/ after experience with Japanese.

The Visual System Is Engaged in Language Production and Perception

Language is ordinarily communicated through an auditory-vocal channel, but deaf individuals communicate through a visual-manual channel. Natural signed languages, such as American Sign Language (Ameslan or ASL), are those invented by the deaf and vary across countries. Deaf infants "babble" with their hands at approximately the same time in development as hearing infants babble orally. Other developmental milestones, such as first words and two-word combinations, also occur on the developmental timetable of hearing infants.

Additional studies indicate that visual information of another kind, the face of the talker, is not only very helpful for communication but also affects the everyday perception of speech. We all experience the benefits of "lip reading" at noisy parties—watching speakers' mouths move helps us understand speech in a noisy environment. The most compelling laboratory demonstration that vision plays a role in everyday speech perception is the illusion that results when discrepant speech information is sent to the visual and auditory modalities. When subjects hear the syllable "ba" while watching a person pronounce "ga" they report hearing an intermediate articulation "da." Such demonstrations support the idea that speech categories are defined both auditorily and visually and that perception is governed by both sight and sound.

Prosodic Cues Are Learned as Early as In Utero

Long before infants recognize that things and events in the world have names, they memorize the global sound patterns typical in their language. Infants learn such prosodic cues as pitch, duration, and loudness changes. In English, for example, a strong/weak pattern of stress is typical—as in the words "BAby," "MOMmy," "TAble," and "BASEball"—whereas in some languages, a weak/strong pattern predominates. Six- and 9-month-old infants given a listening choice between words in English or Dutch show a listening preference for native-language words at the age of 9 months (but not at 6 months).

Prosodic cues can convey both linguistic information (differences in intonation and tone in languages such as Chinese) and paralinguistic information, such as the emotional state of the speaker. Even in utero fetuses learn prosodic cues by listening to their mother's speech. Certain sounds are transmitted through bone conduction to the womb; these are typically intense (above 80 dB), low-frequency sounds (particularly below 300 Hz, but as high as 1,000 Hz with some attenuation). Thus, the prosodic patterns of speech, including voice pitch and the stress and intonation patterns characteristic of a particular language and speaker, are transmitted to the fetus, while the sound patterns that convey phonetic units and words are greatly attenuated. At birth, infants demonstrate having learned this prosodic information by their preference for (1) the language spoken by their mothers during pregnancy, (2) their mother's voice over that of another female, and (3) stories with a distinct tempo and rhythm read out loud by the mother during the last 10 weeks of pregnancy.

Transitional Probabilities Help Distinguish Words in Continuous Speech

Seven- to 8-month-old infants learn to recognize words using the probability that one syllable will follow another. Such transitional probabilities between syllables within a word are high because the sequential order remains fixed. In the word *potato*, for example, the syllable "ta" always follows the syllable "po" (probability of 1.0). Between words, on the other hand, as between "hot" and "po" in the string *hot potato*, are much lower transitional probabilities.

Psychologist Jenny Saffran showed that infants treat phonetic units and syllables with high transitional probabilities as word-like units. In one experiment, infants heard 2-minute strings of pseudo-words, such as *tibudo*, *pabiku*, *golatu*, and *daropi*, without any acoustic breaks between them. They were then tested for recognition of these pseudo-words as well as new ones formed by combining the last syllable of one word with the two initial syllables of another word (such as *tudaro* formed from *golatu* and *daropi*). Infants recognized the original pseudo-words but not the new combinations they had not been previously exposed to, indicating that they used transitional probabilities to identify words.

These forms of learning clearly do not involve Skinnerian reinforcement. Caretakers do not manage the contingencies and gradually shape through reinforcement the statistical analyses performed by infants. Conversely, language learning by infants also does not appear to reflect a process in which innately provided options are chosen based on language experience. Rather, infants learn language implicitly through detailed analysis of the patterns of statistical variation in the natural speech they hear and sophisticated analysis of information provided through social interaction (eg, eye gaze). The learning of these patterns in turn alters perception to favor the native language. In summary, both the statistical properties of language and the social cues provided during language interactions help infants learn. Language evolved to capitalize on the kinds of cues that infants are innately able to recognize. This mirrors the argument that the development of phonetic units was significantly influenced by the features of mammalian hearing, ensuring that infants would find it easy to discriminate phonemes, the fundamental units of meaning in language.

There Is a Critical Period for Language Learning

Children learn language more naturally and efficiently than adults, a paradox given that the cognitive skills of adults are superior. Why should this be the case?

Many consider language acquisition to be an example of a skill that is learned best during a critical period in development. Eric Lenneberg proposed that maturational factors at puberty cause a change in the neural mechanisms that control language acquisition. Evidence supporting this view comes from classic studies of Chinese and Korean immigrants to the United States who had been immersed in English at ages ranging from 3 to 39 years. When asked to identify errors in sentences containing grammatical mistakes, an easy task for native speakers, the responses of second-language learners declined with the age of arrival in the United States. A similar trend emerges when one compares individuals exposed to ASL from birth to those exposed between 5 and 12 years of age. Those exposed from birth were best at identifying errors in ASL, those exposed at age 5 were slightly poorer, and those exposed after the age of 12 years were substantially poorer.

What restricts our ability to learn a new language after puberty? Developmental studies suggest that prior learning plays a role. Learning a native language produces a neural commitment to detection of the acoustic patterns of that language, and this commitment interferes with later learning of a second language. Early exposure to language results in neural circuitry that is "tuned" to detect the phonetic units and prosodic patterns of that language. Neural commitment to native language enhances the ability to detect patterns based on those already learned (eg, phonetic learning supports word learning) but reduces the ability to detect patterns that do not conform. Learning the motor patterns required to speak a language also results in neural commitment. The motor patterns learned for one language (eg, lip rounding in French) can interfere with those required for pronunciation of a second language (eg, English) and thus can hinder efforts to pronounce the second language without an accent. Early in life, two or more languages can be easily learned because interference effects are minimal until neural patterns are well established.

Neurobiologist Takao Hensch has been working on identifying the chemical switches that open and close neurodevelopmental critical periods in learning, including those in animals and humans. Hensch has found that the neurotransmitter γ-aminobutyric acid (GABA) opens the critical period by inhibiting the firing of excitatory neurons, bringing them into balance with the firing of inhibitory neurons so as to create an excitatory–inhibitory (EI) balance. Studies testing this hypothesis in humans are difficult to conduct, but investigations on the infants of mothers who altered the EI balance of the fetus during pregnancy by taking psychotropic medications (serotonin reuptake inhibitors [SRIs]) for depression support the EI hypothesis. One of fluoxetine's off-target effects is to increase the sensitivity of some GABA receptors to GABA. When compared to infants of depressed mothers who were not exposed prenatally to SRIs and control mothers without depression or SRIs, infants exposed prenatally to SRIs showed an accelerated phonetic learning process, indicating that the well-established timing of the early transition in infants' phonetic perception can be altered.

We do not completely lose the ability later in life to learn a new language, but it is far more difficult. Regardless of the age at which learning begins, second-language learning is improved by a training regimen that mimics critical components of early learning—long periods of listening in a social context (immersion), the use of both auditory and visual information, and exposure to simplified and exaggerated speech resembling "parentese."

The "Parentese" Speaking Style Enhances Language Learning

Everyone agrees that when adults talk to their children they sound unusual. Discovered by linguists and anthropologists in the early 1960s as they listened to languages spoken around the world, "motherese" (or "parentese," as fathers produce it as well) is a special speaking style used when addressing infants and young children. Parentese has a higher pitch, slower tempo, and exaggerated intonation contours, and is easily recognized. Compared to adult-directed speech, the pitch of the voice is increased on average by an octave both in males and in females. Phonetic units are spoken more clearly and are acoustically exaggerated, thus increasing the acoustic distinctiveness of phonetic units. Adults speaking to infants exaggerate just those features of speech that are critical to their native language. For example, when talking to their infants, Chinese mothers exaggerate the four tones in Mandarin that are critical to word meaning.

When given a choice, infants prefer listening to infant-directed rather than adult-directed speech. When infants are allowed to activate recordings of infant-directed or adult-directed speech by turning their head left or right, they will turn in whatever direction is required to turn on infant-directed speech.

Recent research by psychologists Nairan Ramirez-Esparza and Adrian Garcia-Sierra shows that the degree to which parentese is used in language spoken to infants at 11 and 14 months of age at home is strongly correlated with a child's language development by the age of 24 months and remains strongly correlated at the age of 36 months. This relationship holds for both monolingual and bilingual children. However, in bilingual children, early advances in the two languages differ depending on the language spoken in parentese. For example, Spanish-language parentese enhances a child's behavioral and neural responses to Spanish, but not English, and vice versa. Children raised in families in which the amount of language exposure and the use of parentese are low often show deficits in language and literacy by the time they enter school, and these deficits correlate with decreased functional activation in brain areas related to language.

Successful Bilingual Learning Depends on the Age at Which the Second Language Is Learned

How does the brain handle two languages? Behavioral data show that if exposure to two languages begins at birth, children reach the milestones of language at the same age as their monolingual peers—they coo, babble, and produce words at the benchmark ages seen in monolinguals. The idea that bilingual experience produces "confusion" has been debunked by studies that measure "conceptual" vocabulary, that is, word knowledge regardless of the language the child uses to express that knowledge. Older studies measured words in only one of the infants' two languages, and such word counts often showed decreased vocabulary when compared to monolinguals. Conceptual vocabulary scores show that bilingual children's vocabulary counts meet or exceed those of their monolingual peers.

Exposure to a second language after puberty shows limitations in the degree to which the new language can be learned. Whether subjects are tested on phonological rules, morphological endings, or syntax, the ability to learn a new language appears to decline every 2 years after the age of 7 years, indicating that acquisition of a second language after puberty is quite difficult.

Brain measures on bilingual infants reflect these behavioral data. Psychologist Naja Ferjan Ramirez used MEG to show that activation of the superior temporal area in 11-month-old infants exposed to two languages (English and Spanish) from birth is the same for the sounds of both languages and that brain responses to English sounds are equivalent to those of age-matched monolingual infants for English. Bilingual infants listening to speech also exhibit greater activation in the prefrontal cortex, a region mediating attention, when compared to monolingual infants; this finding is consistent with the fact that bilingual children (adults as well) demonstrate superior cognitive skills related to attention. Arguably, listening to two languages requires multiple shifts in attention to activate one language over another.

If a second language is acquired later in development, the age at which exposure occurs and the degree of eventual proficiency affect how the brain processes both languages. In "late" bilinguals (those who learned a second language after puberty), the second language and native language are processed in spatially separated areas in the language-sensitive left frontal region. In "early" bilinguals (those who acquired both languages as children), the two languages are processed in the same left frontal area.

A New Model for the Neural Basis of Language Has Emerged

Numerous Specialized Cortical Regions Contribute to Language Processing

The classical Wernicke-Geschwind neural model of language was based on the works of Broca (1861), Wernicke (1874), Lichtheim (1885), and Geschwind (1970). In the Wernicke-Geschwind model, acoustic cues contained in spoken words were processed in auditory pathways and relayed to Wernicke's area, where the meaning of a word was conveyed to higher brain structures. The arcuate fasciculus was assumed to

Table 55–1 Differential Diagnosis of the Main Types of Aphasia

Type of aphasia	Speech	Comprehension	Capacity for repetition	Other signs	Region affected
Broca	Nonfluent, effortful	Largely preserved for single words and grammatically simple sentences	Impaired	Right hemiparesis (arm > leg); patient aware of defect and can be depressed	Left posterior frontal cortex and underlying structures
Wernicke	Fluent, abundant, well articulated, melodic	Impaired	Impaired	No motor signs; patient can be anxious, agitated, euphoric, or paranoid	Left posterior superior and middle temporal cortex
Conduction	Fluent with some articulatory defects	Intact or largely preserved	Impaired	Often none; patient can have cortical sensory loss or weakness in right arm	Left superior temporal and supramarginal gyri
Global	Scant, nonfluent	Impaired	Impaired	Right hemiplegia	Massive left perisylvian lesion
Transcortical motor	Nonfluent, explosive	Intact or largely preserved	Intact or largely preserved	Sometimes right-sided weakness	Anterior or superior to Broca's area
Transcortical sensory	Fluent, scant	Impaired	Intact or largely preserved	No motor signs	Posterior or inferior to Wernicke's area

be a unidirectional pathway that brought information from Wernicke's area to Broca's area to enable speech production. Both Wernicke's and Broca's areas interacted with association areas. The Wernicke-Geschwind model formed the basis for a practical classification of the aphasias that clinical neurologists still use today (Table 55–1).

Advancements in basic and clinical neuroscience, the advent of more sophisticated functional brain imaging tools, advanced methods for structural brain imaging, and an increasing number of studies that combine brain and behavioral measures have resulted in the development of a new "dual-stream" model. In the dual-stream model, the processing of language is thought to involve large-scale networks that are composed of different brain areas, each with a specialized function, and the white matter tracts that connect them.

This dual-stream model of language processing is similar to the well-established "what" and "where" dual-stream model of the visual system. The existence of two cortical streams of auditory information processing was first postulated by Josef Rauschecker. Gregory Hickok and David Poeppel further elaborated the dual-stream model, and it has since been even further expanded upon by Angela Friederici as well as others studying the neurobiology of language. Figure 55–4 shows the basic components of the dual-stream model.

Compared to the classic Wernicke-Geschwind model, the dual-stream model comprises a larger number of cortical areas that are more widely distributed in the brain and adds critical connecting bidirectional pathways between specialized brain regions. These improvements in the model for language processing are due to advances in structural brain imaging techniques, such as DTI and diffusion-weighted imaging, which provide quantitative measures on a microscopic scale of the white matter in fascicles that connect various cortical areas and allow for the detailed delineation of neural tracts throughout the brain (tractography).

In the dual-stream model, initial spectrotemporal processing of auditory speech sounds is performed bilaterally in the auditory cortex. This information is then communicated to the posterior superior temporal gyrus bilaterally, where phonological-level processing occurs. Language processing then diverges into a dorsal "sensorimotor stream," which maps sound to articulation, and a ventral "sensory-conceptual" stream, which maps sound to meaning.

The bidirectional dorsal stream connects auditory speech information with motor plans that produce speech. The dorsal stream passes above the lateral ventricles and maps sounds onto articulatory representations, connecting regions of the inferior frontal lobe, premotor cortex, and insula (all involved in speech articulation) to the region that is classically recognized as Wernicke's area. It is considered to comprise two pathways: Dorsal pathway 1 connects the posterior

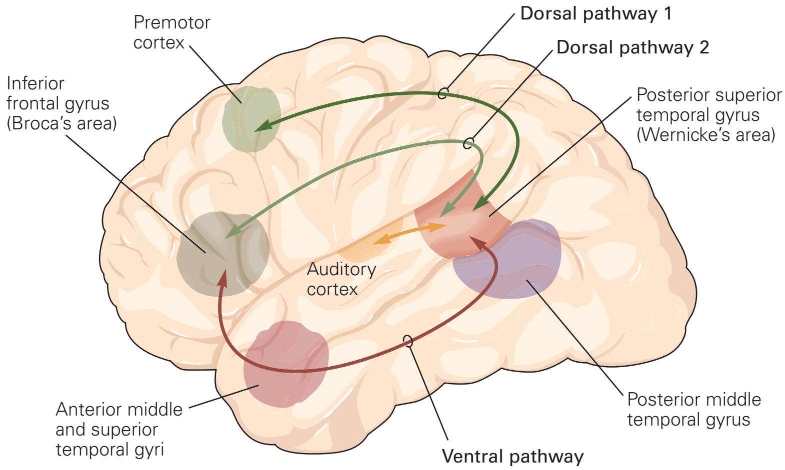


Figure 55–4 **Dual-stream model of language processing.** Temporal and spectral analyses of speech signals occur bilaterally in the auditory cortex followed by phonological analysis in the posterior superior temporal gyri (**yellow arrow**). Processing then diverges into two separate pathways: a dorsal stream that maps speech sounds to motor programs and a ventral stream that maps speech sounds to meaning. The dorsal pathway is strongly left hemisphere dominant and has segments that extend to the premotor cortex (dorsal pathway 1) and to the posterior inferior frontal cortex (dorsal pathway 2). The ventral pathway occurs bilaterally and extends to the anterior temporal lobe and the posterior inferior frontal cortex. (Adapted, with permission, from Hickok and Poeppel 2007, and Skeide and Friederici 2016.)

superior temporal gyrus to the premotor cortex, and dorsal pathway 2 connects the posterior superior temporal gyrus to Broca's area. Pathway 2 is involved in higher-order analysis of speech, such as discriminating subtle differences in meaning based on grammar and interpreting language using more complex concepts. The dorsal stream is strongly left hemisphere dominant. The arcuate fasciculus and the superior longitudinal fasciculus are white matter fiber tracts that mediate communication along the dorsal stream.

The ventral stream passes below the Sylvian fissure and is composed of regions of the superior and middle temporal lobes as well as regions of the posterior inferior frontal lobe. This stream conveys information for auditory comprehension, which requires transformation of the auditory signal to representations in a mental lexicon, a "brain-based dictionary" that links individual word forms to their semantic meaning. This stream comprises the inferior fronto-occipital fasciculus, the uncinate fasciculus, and the extreme fiber capsule system and is largely bilaterally represented.

The cortical brain regions included in the dual-stream model also interact with spatially distributed regions throughout both hemispheres of the brain that provide additional information crucial for language processing. These regions include the prefrontal cortex and cingulate cortices, which exert executive control and mediate attentional processes, respectively, as well as regions in the medial temporal, frontal, and parietal areas involved in memory retrieval.

The Neural Architecture for Language Develops Rapidly During Infancy

The study of language development in infancy requires a methodology that documents significant changes in behavior and links those changes to changes in brain function and morphology over time. Neuroimaging methods for the infant brain have improved substantially over the past decade, allowing for a detailed assessment of the progression of development of the specialized regions and structural connections required by the language network. For example, developmental neuroscientists have created models of the average infant brain and brain atlases for the infant brain at 3 and 6 months of age. These models indicate that brain structures essential to language processing in adulthood, such as the inferior frontal cortex, premotor cortex, and superior temporal gyrus, support speech processing in early infancy. Studies using DTI and tractography indicate that the arcuate fasciculus and the uncinate fasciculus connect language regions by 3 months of age.

The development of the neural substrates for language in 1- to 3-day-old infants has been studied in depth by Daniela Perani using fMRI and DTI. Perani's fMRI work reveals that listening to speech activates the infant superior temporal gyrus bilaterally and that in the left hemisphere this activation extends to the planum temporale, inferior frontal gyrus, and inferior parietal lobe. Perani's DTI studies of the same newborn infants demonstrate weak intrahemispheric connections, but strong connections between the hemispheres. Nevertheless, the ventral fiber tract connecting the ventral portion of the inferior frontal gyrus via the extreme fiber capsule system to the temporal cortex is evident in newborns and in both hemispheres. The dorsal pathway connecting the temporal cortex to the premotor cortex is also present in the newborns, although the dorsal tract that connects the temporal cortex to Broca's area in adults is not detectable in newborns. These early connections between sensory areas