Chapter 55: Language

Introduction

LANGUAGE IS UNIQUELY HUMAN and arguably our greatest skill and our highest achievement. Despite its complexity, all typically developing children master it by the age of 3. What causes this universal developmental phenomenon, and why are children so much better at acquiring a new language than adults? What brain systems are involved in mature language processing, and are these systems present at birth? How does brain damage produce the various disorders of language known as the aphasias?

For centuries, these questions about language and the brain have prompted vigorous debate among theorists. In the last decade, however, an explosion of information regarding language has taken us beyond the nature–nurture debates and beyond the standard view that a few specialized brain areas are responsible for language. Two factors have brought about this change.

First, functional brain imaging techniques such as positron emission tomography (PET), functional magnetic resonance imaging (fMRI), electroencephalography (EEG), and magnetoencephalography (MEG) have allowed us to examine activation patterns in the brain while a person carries out language tasks—naming objects or actions, listening to sounds or words, and detecting grammatical anomalies. The results of these studies reveal a far more complex picture than the one first proposed by Carl Wernicke in 1874. Moreover, structural brain imaging techniques, such as diffusion tensor imaging (DTI), tractography, and quantitative magnetic resonance imaging (qMRI), have revealed a network of connections that link specialized language areas in the brain. These discoveries are taking us beyond previous, simpler views of the neural underpinnings of language processing and production that assumed involvement of only a few specific brain areas and connections.

Second, behavioral and brain studies of language acquisition show that infants begin to learn language earlier than previously thought, and in ways that had not been previously envisioned. Well before children produce their first words, they learn the sound patterns underlying the phonetic units, words, and phrase structure of the language they hear. Listening to language alters the infant brain early in development, and early language learning affects the brain for life.

Taken together, these advances are shaping a new view of the functional anatomy of language in the brain as a complex and dynamic network in the adult brain, one in which multiple, spatially distributed brain systems cooperate functionally via long-distance neural fascicles (axon fiber bundles). This mature network arises from the considerable brain structure and function in place at birth and develops in conjunction with powerful innate learning mechanisms responsive to linguistic experience. This new view of language encompasses not only its development and mature state, but also its dissolution when brain damage leads to aphasia.

Humans are not the only species to communicate. Passerine birds attract mates with songs, bees code the distance and direction to nectar by dancing, and monkeys signal a desire for sexual contact or fear at the approach of an enemy with coos and grunts. With language, we accomplish all of the above and more. We use language to provide information and express our emotions, to comment on the past and future, and to create fiction and poetry. Using sounds that have only an arbitrary association with the meanings they convey, we talk about anything and everything. No animal has a communication system that parallels human language either in form or in function. Language is the defining characteristic of humans, and living without it creates a totally different world, as patients with aphasia following a stroke experience so heartbreakingly.

Language Has Many Structural Levels: Phonemes, Morphemes, Words, and Sentences

What distinguishes language from other forms of communication? The key feature is a finite set of distinctive speech sounds or phonemes that can be combined with infinite possibilities. Phonemes are the building blocks of units of significance called morphemes. Each language has a distinctive set of phonemes and rules for combining them into morphemes and words. Words can be combined according to the rules of syntax into an infinite number of sentences.

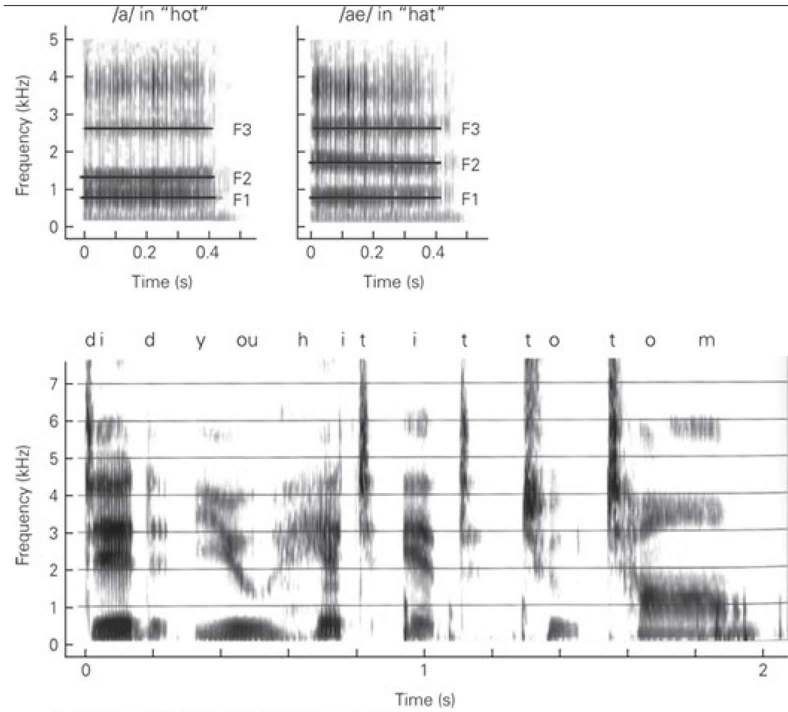
Understanding language presents an interesting set of puzzles, ones that challenge supercomputers. The advent of virtual personal assistants such as Siri and Alexa, based on machine-learning algorithms, has allowed electronic devices to respond to select kinds of human utterances. However, we are still not conversing with computers. Fundamental advances will need to be made before humans can expect to have a conversation with a machine that resembles a conversation you can have with any 3-year-old. Machine-learning solutions do not accomplish their limited responses by mimicking human brain systems used for language, nor do they learn in the ways that human infants learn. Comparing machine-learning approaches (artificial intelligence) and human approaches is of theoretical and practical interest (Chapter 39) and is a hot topic for future research.

Language presents such a complex puzzle because it involves many functionally interconnected levels, starting at the most basic level with the sounds that distinguish words. For example, in English, the sounds /r/ and /1/ differentiate the words *rock* and *lock*. In Japanese, however, this sound change does not distinguish words because the /r/ and /l/ sounds are used interchangeably. Similarly, Spanish speakers distinguish between the words *pano* and *bano*, whereas English speakers treat the /p/ and /b/ sounds at the beginning of these words as the same sounds. Given that many languages use identical sounds but group them differently, children must discover how sounds are grouped to make meaningful distinctions in their language.

Phonetic units are subphonemic. As we have illustrated above with /r/ and /l/, these two sounds are both phonetic units, but their phonemic status differs in English and Japanese. In English, the two are phonemically distinct, meaning that they change the meaning of a word. In Japanese, /r/ and /l/ belong to the same phonemic category and are not distinct. Phonetic units are distinguished by subtle acoustic variations caused by the shape of the vocal tract called *formant frequencies* (Figure 55–1). The patterns and timing of formant frequencies distinguish words that differ in only one phonetic unit, such as the words *pat* and *bat*. In normal speech, formant changes occur very rapidly, on the order of milliseconds. The auditory system has to track these rapid changes in order for an individual 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.

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.)



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.

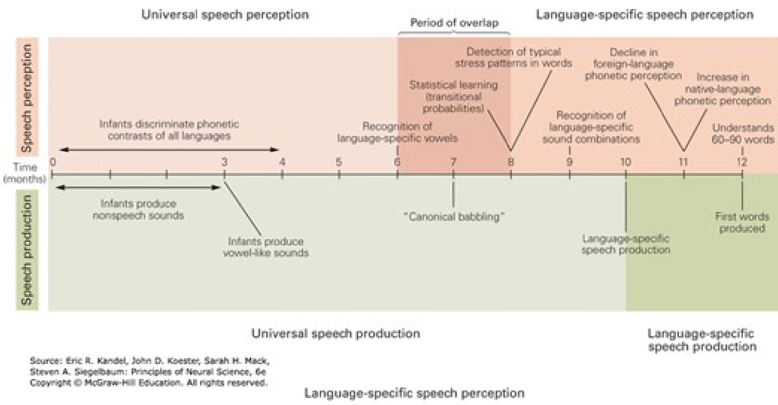
Finally, to create language, words have to be strung together. *Syntax* specifies word and phrase order for a given language. In English, for example, sentences typically conform to a subject-verb-object order (eg, *He eats cake*), whereas in Japanese, it is typically subject-object-verb (eg, *Karewa 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*).

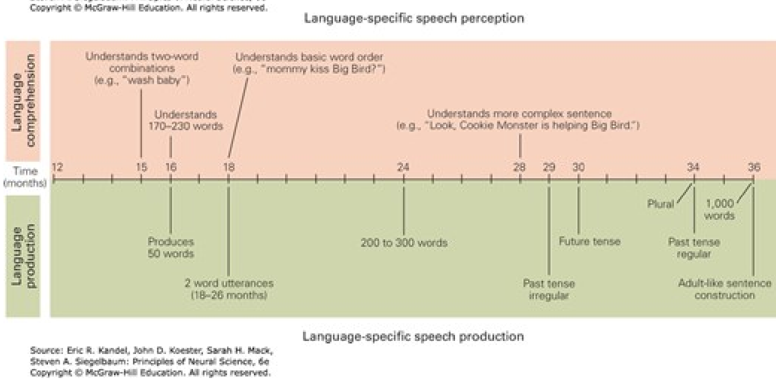
Language Acquisition in Children Follows a Universal Pattern

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.

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.)





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 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.

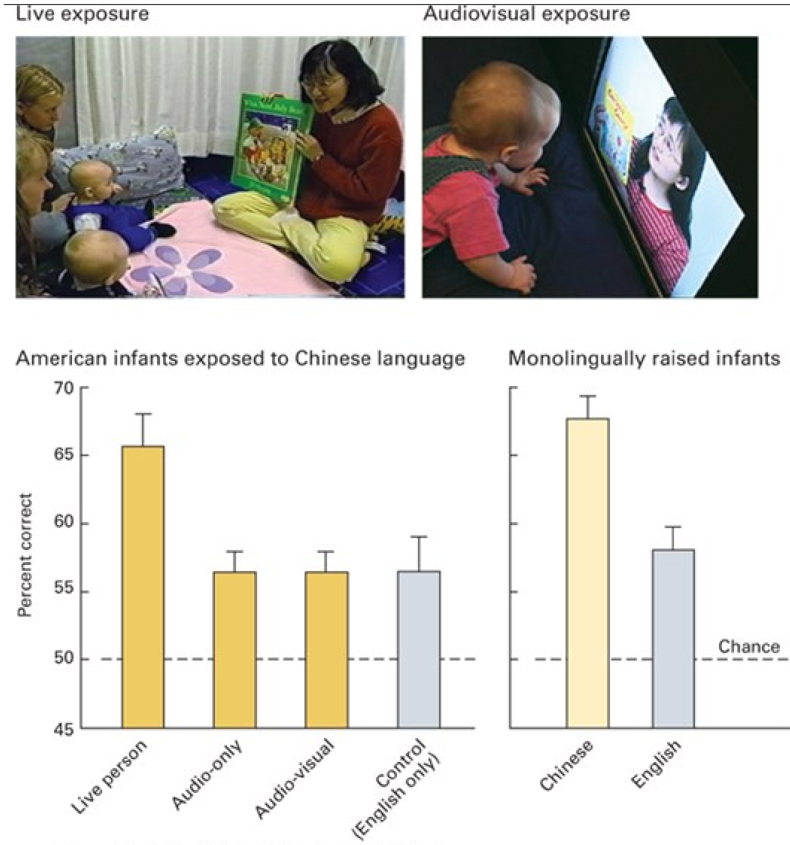
If the second half of the first year is a sensitive period for speech learning, what happens when infants are exposed to a new language during this time? Do they learn? When American infants were exposed to Mandarin Chinese in the laboratory between 9 and 10 months of age, the infants learned if exposure 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.

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.



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 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 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).

Table 55–1

Differential Diagnosis of the Main Types of Aphasia

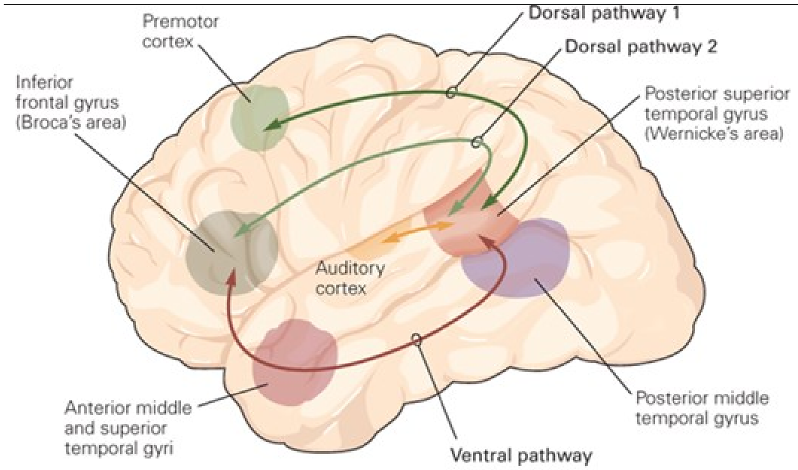
Type of aphasia	Speech	Comprehension	Capacity for repetition	Other signs	Region affected
Broca	Nonfluent, effortful	Largely preserved for single words and grammatically simple sentences	Impaired	Right hemiparesis (arm > leg); patient aware of defect and can be depressed	Left posterior frontal cortex 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

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.

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.)



Source: Eric R. Kandel, John D. Koester, Sarah H. Mack, Steven A. Siegelbaum: Principles of Neural Science, 6e
Copyright © McGraw-Hill Education. All rights reserved.

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 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 and the premotor cortex are important because they may allow the sensory-to-motor mapping essential for the development of early imitation of the sounds and words of the language.

Jens Brauer and colleagues replicated these findings on the development of ventral and dorsal pathways in newborns, revealing the maturational primacy of the ventral connection linking temporal areas to the inferior frontal gyrus. Brauer also verified that the dorsal pathway connects the temporal and premotor cortex at birth and showed that the dorsal pathway to the inferior frontal gyrus develops later. Brauer used the same protocol with children 7 years of age and adults. In 7-year-olds, the dorsal pathway fully connects auditory areas and the inferior frontal gyrus, but in adults, it has more extensive and far-reaching connections.

EEG and MEG functional brain imaging studies on young infants as early as 2 months of age show that the inferior frontal and temporal cortices, implicated in both the classical and contemporary models of language processing, are activated bilaterally by speech—syllables, words, and sentences. This finding supports the hypothesis that left hemisphere specialization increases over time, with syllables showing dominant left hemisphere specialization at the end of the first year, words by the age of 2, and sentences in middle childhood.

EEG and MEG studies of young infants in which infants listen passively to native and nonnative syllables have produced results consistent with the behavioral transitions described earlier in this chapter. Several infant laboratories have shown that brain activity in response to speech, measured early in development, provides sensitive markers that predict language skills several years later. These studies hold promise for the eventual identification of brain measures in infants that indicate risk for developmental disabilities involving language, such as autism spectrum disorder, dyslexia, and specific language impairment. Early identification would allow earlier and more effective interventions for these impairments, improving outcomes for these children and their families.

Studies using functional MEG brain imaging of infants show that at 7 months of age, native and nonnative speech syllables activate not only superior temporal regions of the infant brain but also inferior frontal regions and the cerebellum, forging an association between speech patterns they hear and the motor plans they use to babble and imitate. By 12 months of age, language experience alters the patterns of activation in both sensory and motor brain regions.

Auditory activation becomes stronger for *native* sounds, indicating that brain areas have begun to become specialized for native language phonology. In contrast, motor activation in both Broca's area and the cerebellum is increased in response to *nonnative* sounds, because by 12 months infants have sufficient sensorimotor knowledge to imitate native sounds and some words and have linked stored auditory patterns (words like "cup" and "ball") to the motor plans necessary to produce them. But they cannot make the sensorimotor associations for foreign-language sounds and words because the necessary motor plans cannot be generated. Therefore, we see longer and more diffuse activation as infants struggle to create the motor plans for a sound or word they have never experienced. The importance of motor learning in language development is also shown by longitudinal whole-brain voxel-based morphometry studies of 7-month-old infants showing that gray matter concentrations in the cerebellum correlate with the number of words those infants can produce at 1 year of age.

Over the next 5 years, there is likely to be an explosive increase in brain studies focused on development of the language network. In a number of laboratories, these brain measures will be linked to behavioral measures, enabling the creation of models that delineate how language experience alters the infant brain to increase its specialization for the language or languages to which the child is exposed. The finding that the classic brain regions known to be part of the language network in adults—in particular, the left and right temporal cortices and the left inferior frontal cortex—are already activated by speech at birth recalls Chomsky's view of innate language capabilities.

The Left Hemisphere Is Dominant for Language

Current views of language processing agree that while the neural circuitry necessary for transforming speech sounds to meaning may be present in both hemispheres, the left hemisphere is more highly specialized for language processing. This left hemisphere dominance develops with maturation and learning.

Evidence from a variety of sources suggests that left hemisphere specialization for language develops rapidly in infancy. Word learning represents a case in point. Deborah Mills and her colleagues used event-related potentials to track development of the neural signals generated in response to words that children knew. Her studies showed that both age and language proficiency produce changes in the strength of the neural responses to known words, as well as a change in hemisphere dominance between 13 and 20 months of age. At the earliest age studied, known words activate a broad and bilaterally distributed pattern across the brain. As infants approach 20 months and vocabulary grows, the activation pattern shifts to become left hemisphere dominant in the temporal and parietal regions. In late talkers, this shift is delayed to nearly 30 months. In 24-month-old children with autism, the degree to which this left hemisphere dominance is evident predicts children's linguistic, cognitive, and adaptive abilities at age 6.

Several studies show that immersion in a second language in adulthood produces growth in the superior longitudinal fasciculus, a white matter fiber tract that is important for language. Neuroscientist Ping Mamiya, collaborating with geneticist Evan Eichler, demonstrated, using DTI, that white matter integrity of the superior longitudinal fasciculus in the right hemisphere increased in Chinese college students in proportion to the number of days they spent in an English immersion class and decreased after immersion ended. Moreover, analysis of polymorphisms in the catechol-*O*-methyltransferase (*COMT*) gene showed an effect on this relationship—students with two of the variants demonstrated these changes, while students with the third variant showed no change in white matter properties with language experience.

There is great interest in brain studies investigating the selectivity of the brain mechanisms underlying language. Studies in the visual system by neuroscientist Nancy Kanwisher led to the suggestion that certain visual areas (the fusiform face area) are highly selective for particular stimuli, such as faces. Similar claims have been advanced for brain areas underlying speech analysis. For example, Kanwisher's group has proposed that Broca's area contains many subregions, each highly selective for particular levels of language. Additional studies on selectivity, particularly during development, will be the focus of future studies.

Helen Neville and Laura-Anne Pettito have shown that the left hemisphere is activated not only by auditory stimuli but also by visual stimuli that have linguistic significance. Deaf individuals process sign language in left hemisphere speech-processing regions. Such studies show that the language network processes linguistic information regardless of modality.

Prosody Engages Both Right and Left Hemispheres Depending on the Information Conveyed

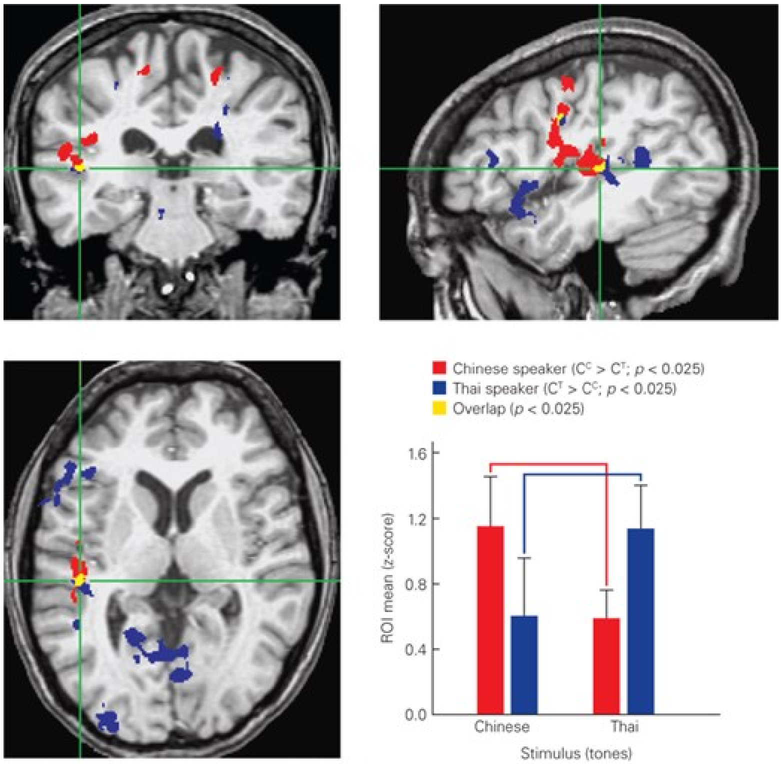
Prosodic cues in language can be linguistic, conveying semantic meaning as tones do in Mandarin Chinese or Thai, as well as paralinguistic, expressing our attitudes and emotions. The pitch of the voice carries both kinds of information, and the brain's processing of each kind of information differs.

Emotional changes in pitch engage the right hemisphere, primarily the right frontal and temporal regions. Emotional information helps convey a speaker's mood and intentions, and this helps interpret sentence meaning. Patients with right hemisphere lesions often produce speech with inappropriate stress, timing, and intonation, and their speech sounds emotionally flat; they also frequently fail to interpret the emotional cues in others' speech.

Semantic changes in pitch involve a different pattern of brain activity, as demonstrated by neuroimaging studies. Jackson Grandour used a novel experimental design using Chinese syllables that carried either their native Chinese tone or the nonnative Thai tone. fMRI results for both Chinese and Thai speakers show higher activation in the left planum temporale for syllables carrying the native tone as opposed to nonnative tone (Figure 55–5). The right hemisphere did not show this double dissociation, supporting the view that language processing occurs in the left hemisphere even for auditory signals typically processed on the right.

Figure 55–5

Brain activation for Chinese and Thai lexical tones revealed by functional magnetic resonance imaging. Language stimuli were composed of Chinese syllables superimposed with either Thai tones (**C**$^{\mathbf{T}}$) or Chinese tones (**C**$^{\mathbf{C}}$). Both native Chinese and native Thai speakers demonstrated a left hemisphere (**LH**) dominance when listening to their native tones. In the Chinese speakers, activation of the left hemisphere was stronger for Chinese tones, whereas in the Thai speakers, activation was stronger for Thai tones. Overlap for the two groups occurs in the left planum temporale and the ventral precentral gyrus. In the left planum temporale (**green crosshairs**), a double dissociation was found between tonal processing and language experience (bar charts). The right hemisphere (**RH**) did not show these effects. (*Top left*, coronal section; *top right*, sagittal section; *bottom left*, axial section.) (Abbreviation: **ROI**, region of interest.) (Adapted, with permission, from Xu et al. 2006. Copyright © 2005 Wiley-Liss, Inc.)



Studies of the Aphasias Have Provided Insights into Language Processing

According to recent estimates, there are more than 795,000 strokes per year in the United States. Aphasia occurs in 21% to 38% of acute strokes and increases the probability of mortality and morbidity. In the past decade, the number of individuals with aphasia grew by more than 100,000 per year. Broca's aphasia, Wernicke's aphasia, and conduction aphasia compose the three classical models of clinical aphasia syndromes. Hickok and Poeppel describe each of these subtypes in the context of the dual-stream model. Accordingly, Broca's aphasia and conduction aphasia are due to sensorimotor integration problems related to damage to the dorsal stream of language processing, whereas Wernicke's aphasia, word deafness, and transcortical sensory aphasia are produced by damage to the ventral stream.

Broca's Aphasia Results From a Large Lesion in the Left Frontal Lobe

Broca's aphasia is a disorder of speech production, including impairments in grammatical processing, caused by lesions of the dorsal stream. When we speak, we rely on auditory patterns stored in the brain. Naming a cup when presented with coffee requires a patient to connect the stored sensory pattern associated with the word "cup" to the motor plans required to hit that auditory target. With Broca's aphasia, the sensory-motor integration necessary for fluent speech production is damaged. Thus, speech is labored and slow, articulation is impaired, and the melodic intonation of normal speech is lacking (Table 55–2). Yet patients sometimes have considerable success at verbal communication because their selection of certain types of words, especially nouns, is often correct. By contrast, verbs and grammatical words such as prepositions and conjunctions are poorly selected or can be missing altogether. Another major sign of Broca's aphasia is a defect in the ability to repeat complex sentences.

Table 55–2

Examples of Spontaneous Speech Production and Repetition for the Primary Types of Aphasia

Type of aphasia	Spontaneous speech	Repetition
	Stimulus (Western Aphasia Battery picnic picture): What do you see in this picture?	Stimulus: "The pastry cook was elated."
Broca	"O, yea. Det's a boy an' a girl . . an' . . a . . car . . house . . light po' (pole). Dog an' a . . boat. 'N det's a . . mm . . a coffee, an' reading. Det's a mm . . a . . det's a boy . . fishin'." (Elapsed time: 1 min 30 s)	"Elated."
Wernicke	"Ah, yes, it's, ah . . several things. It's a girl . . uncurl . . on a boat. A dog . . 'S is another dog . . Uh-oh . . long's . . on a boat. The lady, it's a young lady. An' a man a They were eatin'. 'S be place there. This . . a tree! A boat. No, this is a . . It's a house. Over in here . . a cake. An' it's, it's a lot of water. Ah, all right. I think I mentioned about that boat. I noticed a boat being there. I did mention that before. . Several things down, different things down . . a bat . . a cake . . you have a . ." (Elapsed time: 1 min 20 s)	"/I/ . . no . . In a fog."
Conduction	"Kay. I see a guy readin' a book. See a women /ka . . he . . /pourin' drink or something. An' they're sittin' under a tree. An' there's a . . car behind that an' then there's a house behind th' car. An' on the other side, the guy's flyn' a /fait . . fait/(kite). See a dog there an' a guy down on the bank. See a flag blowin' in the wind. Bunch of /hi . . a . . /trees in behind. An a sailboat on th' river, river . . lake. 'N guess that's about all. . 'Basket there." (Elapsed time: 1 min 5 s)	"The baker was . . What was that last word?" ("Let me repeat it: The pastry cook was elated.") "The baker-er was /vaskerin/ . . uh . ."
Global	(Grunt)	(No response)

Because most patients with Broca's aphasia give the impression of understanding conversational speech, the condition was initially thought to be a deficit of production only. But Broca's aphasics have difficulty comprehending sentences with meanings that depend mostly on grammar. Broca's aphasics can understand *The apple that the girl ate was green*, but have trouble understanding *The girl that the boy is chasing is tall.* This is because they can understand the first sentence without recourse to grammatical rules—girls eat apples but apples do not eat girls; apples can be green but girls cannot. However, they have difficulty with the second sentence because both girls and boys can be tall, and either can chase the other. To understand the second sentence, it is necessary to analyze its grammatical structure, something that Broca's aphasics have difficulty doing.

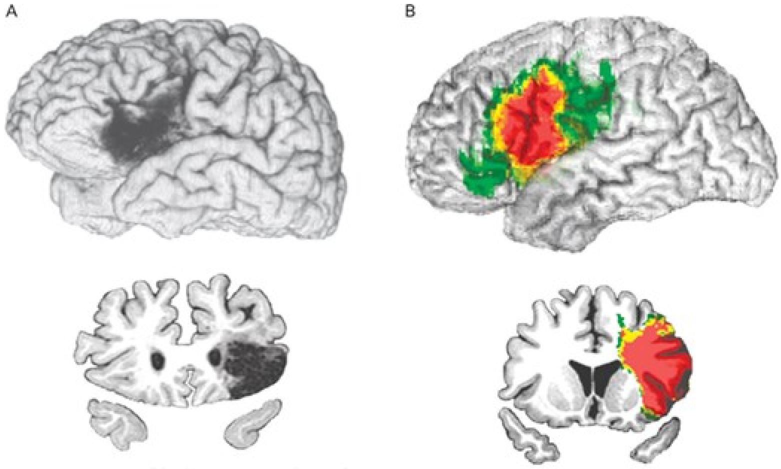
Broca's aphasia results from damage to Broca's area (the left inferior frontal gyrus); the surrounding frontal fields; the underlying white matter, insula, and basal ganglia; and a small portion of the anterior superior temporal gyrus (Figure 55–6). A small sector of the insula, an island of cortex buried deep inside the cerebral hemisphere, can also be included among the neural correlates of Broca's aphasia. Broca's aphasics typically have no difficulty perceiving speech sounds or recognizing their own errors and no trouble in coming up with words. When damage is restricted to Broca's area alone or to its subjacent white matter, the result is the condition of Broca's area aphasia, a milder version of true Broca's aphasia, from which many patients are able to recover.

Figure 55–6

Sites of lesions in Broca's aphasia. (Images used with permission of Hanna and Antonio Damasio.)

A. Top: A three-dimensional magnetic resonance imaging (MRI) reconstruction of a lesion (infarction) in the left frontal operculum (**dark gray**) in a patient with Broca's aphasia. **Bottom:** A coronal MRI section of the same brain through the damaged area.

B. Top: A three-dimensional MRI overlap of lesions in 13 patients with Broca's aphasia (**red** indicates that lesions in five or more patients share the same pixels). **Bottom:** A coronal MRI section of the same composite brain image through the damaged area.



Wernicke's Aphasia Results From Damage to Left Posterior Temporal Lobe Structures

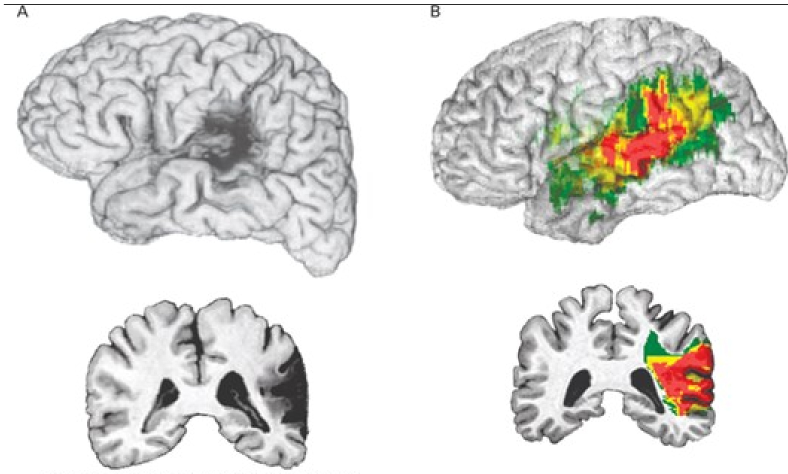
Wernicke's aphasics have difficulty comprehending the sentences uttered by others, and damage occurs in areas of the brain that subserve grammar, attention, and word meaning. Wernicke's aphasia can be caused by damage to different levels of the ventral stream, where auditory information is linked to word knowledge. It is usually caused by damage to the posterior section of the left auditory association cortex, although in severe cases, the middle temporal gyrus and white matter are involved (Figure 55–7).

Figure 55–7

Sites of lesions in Wernicke's aphasia. (Images reproduced, with permission, from Hanna and Antonio Damasio.)

A. Top: Three-dimensional magnetic resonance imaging (MRI) reconstruction of a lesion (an infarction) in the left posterior and superior temporal cortex (**dark gray**) in a patient with Wernicke's aphasia. **Bottom:** Coronal MRI section of the same brain through the damaged area.

B. Top: Three-dimensional MRI overlap of lesions in 13 patients with Wernicke's aphasia obtained with the MAP-3 technique (**red** indicates that five or more lesions share the same pixels). **Bottom:** Coronal MRI section of the same composite brain image through the damaged area.



Source: Eric R. Kandel, John D. Koester, Sarah H. Mack, Steven A. Siegelbaum: Principles of Neural Science, 6e Copyright © McGraw-Hill Education. All rights reserved.

Patients with Wernicke's aphasia can produce speech at a normal rate that sounds effortless, melodic, and quite unlike that of patients with Broca's aphasia. But speech can be unintelligible as well because Wernicke's aphasics often shift the order of individual sounds and sound clusters. These errors are called *phonemic paraphasias* (a paraphasia is substitution of an erroneous phoneme for the correct one). Even when individual sounds are normally produced, Wernicke's aphasics have great difficulty selecting words that accurately represent their intended meaning (known as a *verbal* or *semantic paraphasia*). For example, a patient might say *headman* when they mean president.

Conduction Aphasia Results From Damage to a Sector of Posterior Language Areas

Conduction aphasia, like Broca's aphasia, is thought to involve the dorsal stream. Speech production and auditory comprehension are less compromised than in the two other major aphasias, but patients cannot repeat sentences verbatim, cannot assemble phonemes effectively (and thus produce many phonemic paraphasias), and cannot easily name pictures and objects (Table 55–2).

Conduction aphasia is caused by damage to the left superior temporal gyrus and the inferior parietal lobe. The damage can extend to the left primary auditory cortex, the insula, and the underlying white matter. Large lesions in the Sylvian parietal temporal area, situated in the middle of the network of auditory and motor regions, are consistent with the idea that the damage occurs in the dorsal stream. Damage to left hemisphere auditory regions often produces speech production deficits, supporting the idea that sensory systems participate in speech production. Such lesions interrupt the interfaces linking auditory representations of words and the motor actions used to produce them. The damage compromises white matter (dorsal stream) and affects feedforward and feedback projections that interconnect areas of temporal, parietal, insular, and frontal cortex.

Global Aphasia Results From Widespread Damage to Several Language Centers

Patients with global aphasia are almost completely unable to comprehend language or formulate and repeat sentences, thus combining features of Broca's, Wernicke's, and conduction aphasias. Speech is reduced to a few words at best. The same word might be used repeatedly, appropriately or not, in a vain attempt to communicate an idea. Nondeliberate ("automatic") speech may be preserved, however. This includes stock expletives (which are used appropriately and with normal phonemic, phonetic, and inflectional structures), routines such as counting or reciting the days of the week, and the ability to sing previously learned melodies and their lyrics. Auditory comprehension is limited to a small number of words and idiomatic expressions.

Classic global aphasia involves damage to the inferior frontal and parietal cortices (as seen in Broca's aphasia), the auditory cortex and the insula (as seen in conduction aphasia), and the posterior superior temporal cortex (as seen in Wernicke's aphasia). Subcortical regions, such as the basal ganglia, are often affected as well. Such widespread damage is typically caused by a stroke in the region supplied by the middle cerebral artery. Weakness in the right side of the face and paralysis of the right limbs accompany classic global aphasia.

Transcortical Aphasias Result From Damage to Areas Near Broca's and Wernicke's Areas

Aphasias can be caused by damage not only to speech centers of the cortex but also to pathways that connect those components to the rest of the brain. Transcortical aphasia can be either motor or sensory. Patients with transcortical motor aphasia speak nonfluently, but they can repeat sentences, even very long sentences. Transcortical motor aphasia has been linked to damage to the left dorsolateral frontal area, a patch of association cortex anterior and superior to Broca's area, although there can be substantial damage to Broca's area itself. The left dorsolateral frontal cortex is involved in the allocation of attention and the maintenance of higher executive abilities, including the selection of words.

Transcortical motor aphasia can also be caused by damage to the left supplementary motor area, located high in the frontal lobe, directly in front of the primary motor cortex and buried mesially between the hemispheres. Electrical stimulation of the area in nonaphasic surgery patients causes the patients to make involuntary vocalizations or to be unable to speak, and functional neuroimaging studies have shown it to be activated during speech production. Thus, the supplementary motor area appears to contribute to the initiation of speech, whereas the dorsolateral frontal regions contribute to ongoing control of speech, particularly when the task is difficult.

Transcortical sensory aphasics have fluent speech, impaired comprehension, and great trouble naming things. These patients have deficits in semantic retrieval, without significant disruption of syntactic and phonological abilities.

Transcortical motor and sensory aphasias are caused by damage that spares the arcuate fasciculus and the dorsal stream. Transcortical aphasias are thus the complement of conduction aphasia, behaviorally and anatomically. Transcortical sensory aphasia appears to be caused by damage to the ventral stream, affecting parts of the junction of the temporal, parietal, and occipital lobes, which connect the perisylvian language areas with the parts of the brain responsible for word meaning.

Less Common Aphasias Implicate Additional Brain Areas Important for Language

Several other language-related regions in the cerebral cortex and subcortical structures, for example, the anterior temporal and inferotemporal cortex, have only recently become associated with language. Damage to the left temporal cortex causes severe and pure naming defects—impairments of word retrieval without any accompanying grammatical, phonemic, or phonetic difficulty.

When the damage is confined to the left temporal pole, the patient has difficulty recalling the names of unique places and persons but not the names of common things. When the lesions involve the mid-temporal sector, the patient has difficulty recalling both unique and common names. Finally, damage to the left posterior inferotemporal sector causes a deficit in recalling words for particular types of items—tools and utensils—but not words for natural or unique things. Recall of words for actions or spatial relationships is not compromised (Figure 55–8).

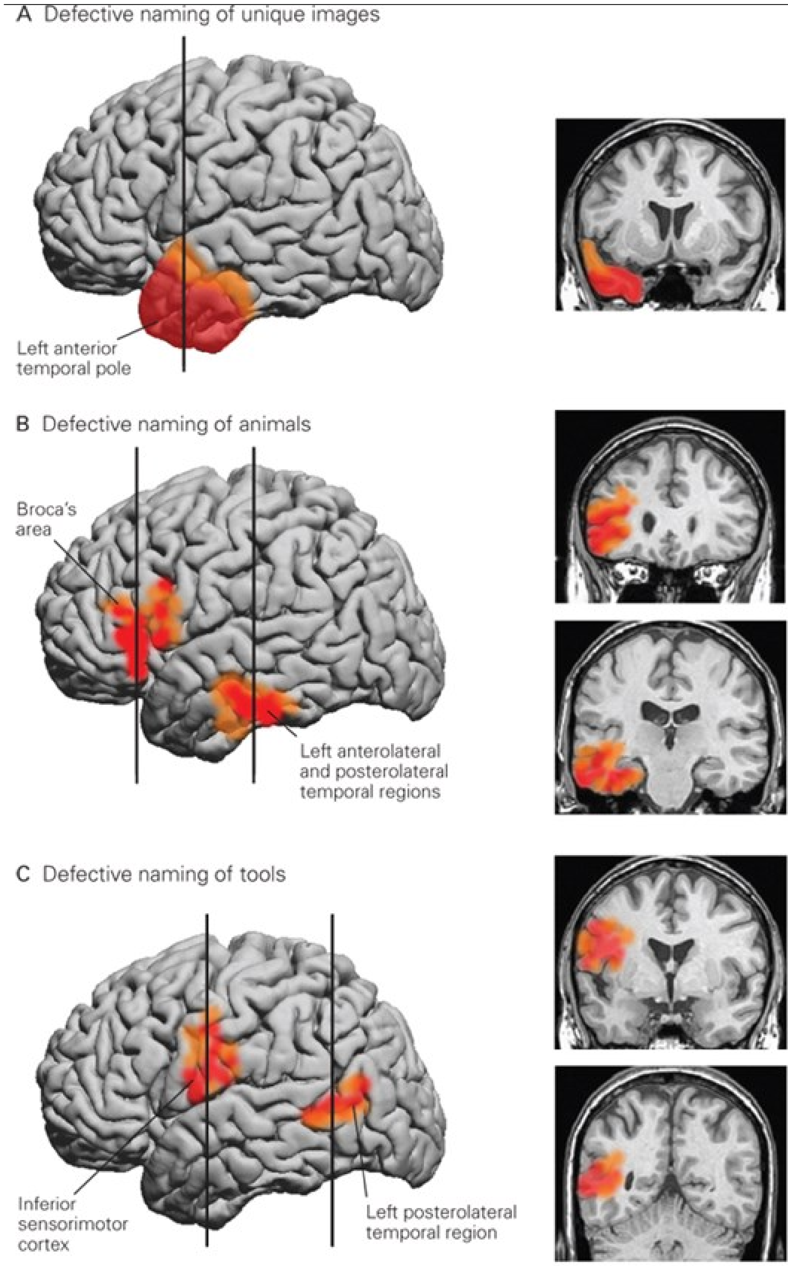
Figure 55–8

Regions of the brain other than Broca's and Wernicke's areas involved in language processing. Functional magnetic resonance imaging was used to study patients with selected brain lesions. (Images reproduced, with permission, from Hanna and Antonio Damasio.)

A. The region of maximal overlap of lesions associated with impaired naming of unique images, such as the face of a person, is the left anterior temporal pole.

B. The sites of maximal overlap of lesions associated with impaired naming of nonunique animals are the left anterolateral and posterolateral temporal regions as well as Broca's region.

C. The sites of maximal overlap of lesions associated with deficits in naming of tools are the left sensorimotor cortex and left posterolateral temporal cortex.



The left temporal cortex contains neural systems that hold the key to retrieving words denoting various categories of things ("tools," "eating utensils"), but not words denoting actions ("walking," "riding a bicycle"). These findings were obtained not only from studies of patients with brain lesions resulting from stroke, head injury, herpes encephalitis, and degenerative processes such as Alzheimer disease, but also from functional imaging studies of typical individuals and from electrical stimulation of these same areas of temporal cortex during surgery.

Areas of frontal cortex in the mesial surface of the left hemisphere, which include the supplementary motor area and the anterior cingulate region, play an important role in the initiation and continuation of speech. Damage in these areas impairs the initiation of movement (akinesia) and causes mutism, a complete absence of speech. In aphasic patients, the complete absence of speech is a rarity and is only seen during the very early stages of the condition. Patients with akinesia and mutism fail to communicate by words, gestures, or facial expression because the drive to communicate is impaired, not because the neural machinery of expression is damaged as in aphasia.

Damage to the left subcortical gray nuclei impairs grammatical processing in both speech and comprehension. The basal ganglia are closely interconnected with the frontal and parietal cortex and may have a role in assembling morphemes into words and words into sentences, just as they serve to assemble the components of a complex movement into a smooth action.

Highlights

1. Language exists at many levels, each of which has to be mastered during childhood—the elemental phonetic units (vowels and consonants) used to change the meaning of a word, the words themselves, word endings (morphemes) that change tense and pluralization, and the grammatical rules that allow words to be strung together to create sentences with meaning. By the age of 3, young children, regardless of the language(s) they are learning, have mastered all levels and can carry on a conversation with an adult. No artificially intelligent machine can yet duplicate this feat.
2. The learning strategies used by children to master language under 1 year of age are surprising. Language learning proceeds as infants (1) exploit the statistical properties of speech (distributional frequency patterns of sounds to detect relevant phonetic units and transitional probabilities between adjacent syllables to detect likely words), and (2) exploit the social context in which language occurs by following the eye movements of adults as they refer to objects and actions to learn word–object and word–action correspondences. At early ages, natural language learning requires a social context and social interaction. Infants' strategies are not well described by Skinnerian operant conditioning or by Chomsky's innate representation and selection based on experience. Instead, powerful implicit learning mechanisms that operate in social contexts vault infants forward from the very earliest months of life.
3. Infants' speech production and speech perception skills are "universal" at birth. In speech perception, infants discriminate all sounds used to distinguish words across all languages until the age of 6 months. By 12 months, discrimination for native-language sounds has dramatically increased, whereas discrimination of foreign-language sounds decreases. Production is initially universal as well and becomes language specific by the end of the first year. By the age of 3, infants know 1,000 words. Mastery of grammatical structure in complex sentences continues until the age of 10. Future work will advance the field by linking the detailed behavioral milestones that now exist to functional and structural brain measures to show how the brain's network for language is shaped as a function of language experience.
4. A new "dual-stream" model of language has emerged based on advances in functional neural imaging and structural brain imaging over the past decade. The new model bears similarities to the dual-stream model for the visual system. The dual-stream model for language goes beyond the classic Wernicke-Geschwind model by showing that numerous brain regions and the neural pathways that connect them support sound-to-meaning (ventral) and sound-to-articulation (dorsal) pathways. Refinement in the model will continue as additional studies show relationships between behavioral and brain measures. Future studies will integrate structural and functional brain measures, genetic measures, and behavioral assessments of language processing and of learning, including second language learning in adulthood.
5. Studies on the infant brain reveal a remarkably well-developed set of brain structures and pathways by 3 to 6 months of age. Structural DTI reveals a fully formed ventral pathway at birth and a dorsal pathway that links auditory areas to premotor, but not Broca's, area at birth. EEG and MEG brain imaging studies mirror the transition in phonetic perception between 6 and 12 months of age, a "critical period" for sound learning. MEG brain scans at this period reveal the co-activation of auditory and motor centers when infants hear speech and show changes in both sensory and motor brain areas as a function of experience. The data indicate that dorsal pathways are sufficiently well formed in the first year to support sensory-to-motor connections and imitation learning during this period.
6. Hemispheric specialization generally increases with age and language experience, with initial representation of the areas and pathways represented bilaterally and dominance emerging with language experience. There are differences in the degree of lateralization, however, for various levels of language. The dorsal stream, which mediates auditory-motor representations of speech, is more left lateralized than the ventral stream, which mediates auditory-conceptual representations of words.
7. The classical aphasias—Broca's, Wernicke's, and conduction aphasia—are well described within the context of the dual-stream model of language. Broca's aphasia, with its emphasis on the inability to produce speech but relatively good speech understanding, is seen as a dorsal stream deficit, whereas Wernicke's aphasia, with its emphasis on speech comprehension deficits, is seen as a ventral stream deficit. Conduction aphasia, like Broca's, is viewed as caused by a dorsal stream deficit, with damage that encompasses auditory and motor regions. Future research on aphasia will benefit from additional studies of functional and structural damage that can be combined with detailed behavioral protocols.
8. Future studies will allow detailed comparisons between human and nonhuman brains to reveal the structures and pathways that are uniquely human and subserve language. Future work will also focus on the degree to which language structures in humans are selectively activated by

speech as opposed to other complex auditory sounds and whether adult-level selectivity is present early in development.

9. Human language represents a unique aspect of human cognitive achievement. Understanding the brain systems that allow this cognitive feat in nearly all children, and especially the discovery of biomarkers that identify children who are at risk for developmental disorders of language, will advance brain science and be beneficial for society. Behavioral studies now allow us to connect the dots with regard to how early language experience is linked to advanced language development by the time children enter school. This may lead to language interventions that improve outcomes for all children.

Patricia K. Kuhl

Selected Reading

Brauer J, Anwander A, Perani D, Friederici AD. 2013. Dorsal and ventral pathways in language development. Brain Lang 127:289–295. [PubMed: 23643035]

Buchsbaum BR, Baldo J, Okada K, et al. 2011. Conduction aphasia, sensory-motor integration, and phonological short-term memory—an aggregate analysis of lesion and fMRI data. Brain Lang 119:119–128. [PubMed: 21256582]

Chomsky N. 1959. A review of B. F. Skinner's "Verbal Behavior." Language 35:26–58.

Damasio H, Tranel D, Grabowski TJ, Adolphs R, Damasio AR. 2004. Neural systems behind word and concept retrieval. Cognition 92:179–229. [PubMed: 15037130]

Doupe A, Kuhl PK. 1999. Birdsong and human speech: common themes and mechanisms. Annu Rev Neurosci 22:567–631. [PubMed: 10202549]

Gopnik A, Meltzoff AN, Kuhl PK. 2001. *The Scientist in the Crib: What Early Learning Tells Us About the Mind*. New York: HarperCollins.

Hickok G, Poeppel D. 2007. The cortical organization of speech processing. Nat Rev Neurosci 8:393–402. [PubMed: 17431404]

Iverson P, Kuhl PK, Akahane-Yamada R, et al. 2003. A perceptual interference account of acquisition difficulties for non-native phonemes. Cognition 87:B47–B57. [PubMed: 12499111]

Kuhl PK. 2004. Early language acquisition: cracking the speech code. Nat Rev Neurosci 5:831–843. [PubMed: 15496861]

Kuhl PK, Rivera-Gaxiola M. 2008. Neural substrates of language acquisition. Annu Rev Neurosci 31:511–534. [PubMed: 18558865]

Kuhl PK, Tsao F-M, Liu H-M. 2003. Foreign-language experience in infancy: effects of short-term exposure and social interaction on phonetic learning. Proc Natl Acad Sci U S A 100:9096–9101. [PubMed: 12861072]

Kuhl PK, Williams KA, Lacerda F, Stevens KN, Lindblom B. 1992. Linguistic experience alters phonetic perception in infants by 6 months of age. Science 255:606–608. [PubMed: 1736364]

Perani D, Saccuman MC, Scifo P, et al. 2011. Neural language networks at birth. Proc Natl Acad Sci U S A 108:16056–16061. [PubMed: 21896765]

Pinker S. 1994. *The Language Instinct.* New York: William Morrow.

Skeide MA, Friederici AD. 2016. The ontogeny of the cortical language network. Nat Rev Neurosci 17:323–332. [PubMed: 27040907]

References

Berwick RC, Friederici AD, Chomsky N, Bolhuis JJ. 2013. Evolution, brain, and the nature of language. Trends Cogn Sci 17:89–98. [PubMed: 23313359]

Broca P. 1861. Remarques sur le siege de la faculte du langage article, suivies d'une observation d'aphemie (perte de la parole). Bull Societe Anatomique de Paris 6:330–357.

Buchsbaum BR, Baldo J, Okada K, et al. 2011. Conduction aphasia, sensory-motor integration, and phonological short-term memory: an aggregate analysis of lesion and fMRI data. Brain Lang 119:119–128. [PubMed: 21256582]

Burns TC, Yoshida KA, Hill K, Werker JF. 2007. The development of phonetic representation in bilingual and monolingual infants. App Psycholing 28:455–474.

Damasio AR, Damasio H. 1992. Brain and language. Sci Am 267:88–109.

Damasio AR, Tranel D. 1993. Nouns and verbs are retrieved with differently distributed neural systems. Proc Natl Acad Sci U S A 90:4957–4960. [PubMed: 8506341]

Dronkers NF, Baldo JV. 2009. Language: aphasia. In: LR Squire (ed). *Encyclopedia of Neuroscience* (Vol. 5), pp. 343–348. Oxford: Academic Press.

Dubois J, Hertz-Pannier L, Dehaene-Lambertz G, Cointepas Y, Le Bihan D. 2006. Assessment of the early organization and maturation of infants' cerebral white matter fiber bundles: a feasibility study using quantitative diffusion tensor imaging and tractography. Neuroimage 30:1121–1132. [PubMed: 16413790]

Eimas PD, Siqueland ER, Jusczyk P, Vigorito J. 1971. Speech perception in infants. Science 171:303–306. [PubMed: 5538846]

Fedorenko E, Duncan J, Kanwisher N. 2012. Language-selective and domain-general regions lie side by side within Broca's area. Curr Biol 22:2059–2062. [PubMed: 23063434]

Ferjan Ramirez N, Ramirez RR, Clarke M, Taulu S, Kuhl PK. 2017. Speech discrimination in 11-month-old bilingual and monolingual infants: a magnetoencephalography study. Dev Sci 20:e12427.

Flege JE. 1995. Second language speech learning: theory, findings, and problems. In: W Strange (ed). *Speech Perception and Linguistic Experience*, pp. 233–277. Timonium, MD: York Press.

Flege JE, Yeni-Komshian GH, Liu S. 1999. Age constraints on second-language acquisition. J Mem Lang 41:78–104.

Friederici AD. 2009. Pathways to language: fiber tracts in the human brain. Trends Cog Sci 13:175–181.

Garcia-Sierra A, Ramirez-Esparza N, Kuhl PK. 2016. Relationships between quantity of language input and brain responses in bilingual and monolingual infants. Int J Psychophysiol 110:1–17. [PubMed: 27720996]

Geschwind N. 1970. The organization of language and the brain. Science 170:940–944. [PubMed: 5475022]

Golfinopoulos E, Tourville JA, Guenther FH. 2010. The integration of large-scale neural network modeling and functional brain imaging in speech motor control. Neuroimage 52:862–874. [PubMed: 19837177]

Hickok G, Okada K, Serences JT. 2009. Area Spt in the human planum temporale supports sensory-motor integration for speech processing. J Neurophysiol 101:2725–2732. [PubMed: 19225172]

Johnson J, Newport E. 1989. Critical period effects in second language learning: the influence of maturational state on the acquisition of English as a second language. Cognit Psychol 21:60–99. [PubMed: 2920538]

Knudsen EI. 2004. Sensitive periods in the development of the brain and behavior. J Cogn Neurosci 16:1412–1425. [PubMed: 15509387]

Kuhl PK. 2000. A new view of language acquisition. Proc Natl Acad Sci U S A 97:11850–11857. [PubMed: 11050219]

Kuhl PK, Andruski J, Christovich I, et al. 1997. Cross-language analysis of phonetic units in language addressed to infants. Science 277:684–686. [PubMed: 9235890]

Lenneberg E. 1967. *Biological Foundations of Language*. New York: Wiley.

Lesser RP, Arroyo S, Hart J, Gordon B. 1994. Use of subdural electrodes for the study of language functions. In: A Kertesz (ed). *Localization and Neuro-Imaging in Neuropsychology*, pp. 57–72. San Diego: Academic Press.

Liu H-M, Kuhl PK, Tsao F-M. 2003. An association between mothers' speech clarity and infants' speech discrimination skills. Dev Sci 6:Fl–F10.

Mamiya PC, Richards TL, Coe BP, Eichler EE, Kuhl PK. 2016. Brain white matter structure and COMT gene are linked to second-language learning in adults. Proc Natl Acad Sci U S A 113:7249–7254. [PubMed: 27298360]

Mills DL, Coffey-Corina SA, Neville HJ. 1993. Language acquisition and cerebral specialization in 20-month-old infants. J Cogn Neurosci 5:317–334. [PubMed: 23972220]

Miyawaki K, Jenkins JJ, Strange W, Liberman AM, Verbrugge R, Fujimura O. 1975. An effect of linguistic experience: the discrimination of /r/ and /l/ by native speakers of Japanese and English. Percept Psychophys 18:331–340.

Neville HJ, Coffey SA, Lawson D, Fischer A, Emmorey K, Bellugi U. 1997. Neural systems mediating American Sign Language: effects of sensory experience and age of acquisition. Brain Lang 57:285–308. [PubMed: 9126418]

Newport EL, Aslin RN. 2004. Learning at a distance I. Statistical learning of non-adjacent dependencies. Cogn Psychol 48:127–162. [PubMed: 14732409]

Peterson SE, Fox PT, Posner MI, Mintun M, Raichle ME. 1988. Positron emission tomographic studies of the cortical anatomy of single-word processing. Nature 331:585–589. [PubMed: 3277066]

Petitto LA, Holowka S, Sergio LE, Levy B, Ostry DJ. 2004. Baby hands that move to the rhythm of language: hearing babies acquiring sign language babble silently on the hands. Cognition 93:43–73. [PubMed: 15110725]

Poeppel D. 2014. The neuroanatomic and neurophysiological infrastructure for speech and language. Curr Opin Neurobiol 28:142–149. [PubMed: 25064048]

Price CJ. 2012. A review and synthesis of the first 20 years of PET and fMRI studies of heard speech, spoken language and reading. Neuroimage 62:816–847. [PubMed: 22584224]

Pulvermüller F, Fadiga L. 2010. Active perception: sensorimotor circuits as a cortical basis for language. Nat Rev Neurosci 11:351–360. [PubMed: 20383203]

Raizada RD, Richards TL, Meltzoff A, Kuhl PK. 2008. Socioeconomic status predicts hemispheric specialisation of the left inferior frontal gyrus in young children. Neuroimage 40:1392–1401. [PubMed: 18308588]

Ramirez-Esparza N, Garcia-Sierra A, Kuhl PK. 2014. Look who's talking: speech style and social context in language input are linked to concurrent and future speech development. Dev Sci 17:880–891. [PubMed: 24702819]

Rauschecker JP. 2011. An expanded role for the dorsal auditory pathway in sensorimotor control and integration. Hear Res 271:16–25. [PubMed:

20850511]

Saffran JR, Aslin RN, Newport EL. 1996. Statistical learning by 8-month old infants. Science 274:1926–1928. [PubMed: 8943209]

Saur D, Kreher BW, Schnell S, et al. 2008. Ventral and dorsal pathways for language. Proc Natl Acad Sci U S A 105:18035–18040. [PubMed: 19004769]

Silva-Pereyra J, Rivera-Gaxiola M, Kuhl PK. 2005. An event related brain potential study of sentence comprehension in preschoolers: semantic and morphosyntactic processing. Cogn Brain Res 23:247–258.

Skinner BF. 1957. *Verbal Behavior*. Acton, MA: Copley Publishing Group.

Tsao F-M, Liu H-M, Kuhl PK. 2004. Speech perception in infancy predicts language development in the second year of life: a longitudinal study. Child Dev 75:1067–1084. [PubMed: 15260865]

Weikum WM, Oberlander TF, Hensch TK, Werker JF. 2012. Prenatal exposure to antidepressants and depressed maternal mood alter trajectory of infant speech perception. Proc Natl Acad Sci U S A 109:17221–17227. [PubMed: 23045665]

Weisleder A, Fernald A. 2013. Talking to children matters: early language experience strengthens processing and builds vocabulary. Psychol Sci 24:2143–2152. [PubMed: 24022649]

Wernicke C. 1874. *Der Aphasische Symptomenkomplex: Eine Psychologische Studie auf Anatomischer Basis*. Breslau: Cohn und Weigert.

Xu Y, Gandour J, Talavage T, et al. 2006. Activation of the left planum temporale in pitch processing is shaped by language experience. Hum Brain Mapp 27:173–183. [PubMed: 16035045]

Yeni-Komshian GH, Flege JE, Liu S. 2000. Pronunciation proficiency in the first and second languages of Korean–English bilinguals. Biling Lang Cogn 3:131–149.

Zatorre RJ, Gandour JT. 2008. Neural specializations for speech and pitch: moving beyond the dichotomies. Philos Trans R Soc Lond B Biol Sci 363:1087–1104. [PubMed: 17890188]

Zhao TC, Kuhl PK. 2016. Musical intervention enhances infants' neural processing of temporal structure in music and speech. Proc Natl Acad Sci U S A 113:5212–5217. [PubMed: 27114512]