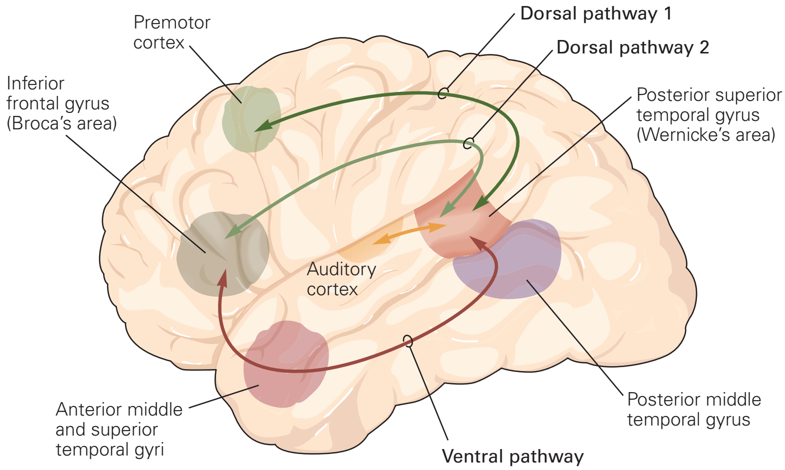


**Figure 55–4 Dual-stream model of language processing.** Temporal and spectral analyses of speech signals occur bilaterally in the auditory cortex followed by phonological analysis in the posterior superior temporal gyri (**yellow arrow**). Processing then diverges into two separate pathways: a dorsal 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 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.

## 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

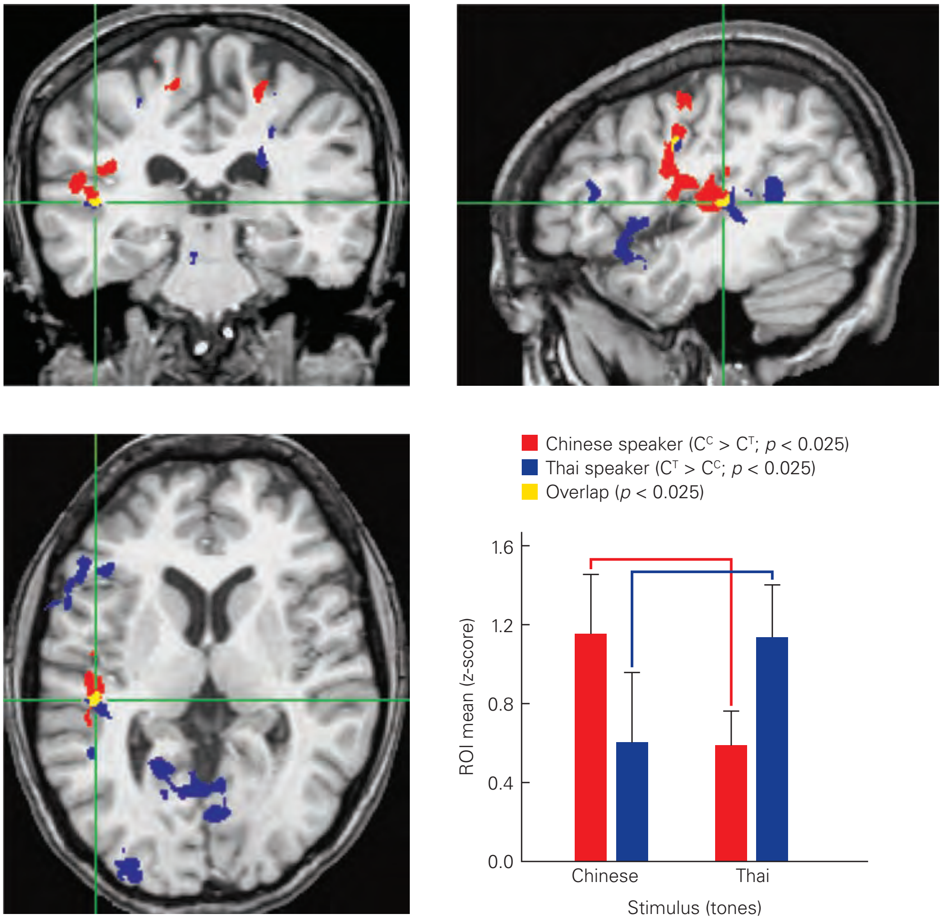


**Figure 55–5 Brain activation for Chinese and Thai lexical tones revealed by functional magnetic resonance imaging.** Language stimuli were composed of Chinese syllables superimposed with either Thai tones (**$C^T$**) or Chinese tones (**$C^C$**). Both native Chinese and native Thai speakers demonstrated 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.)

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.

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

**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) |

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.

### 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).

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

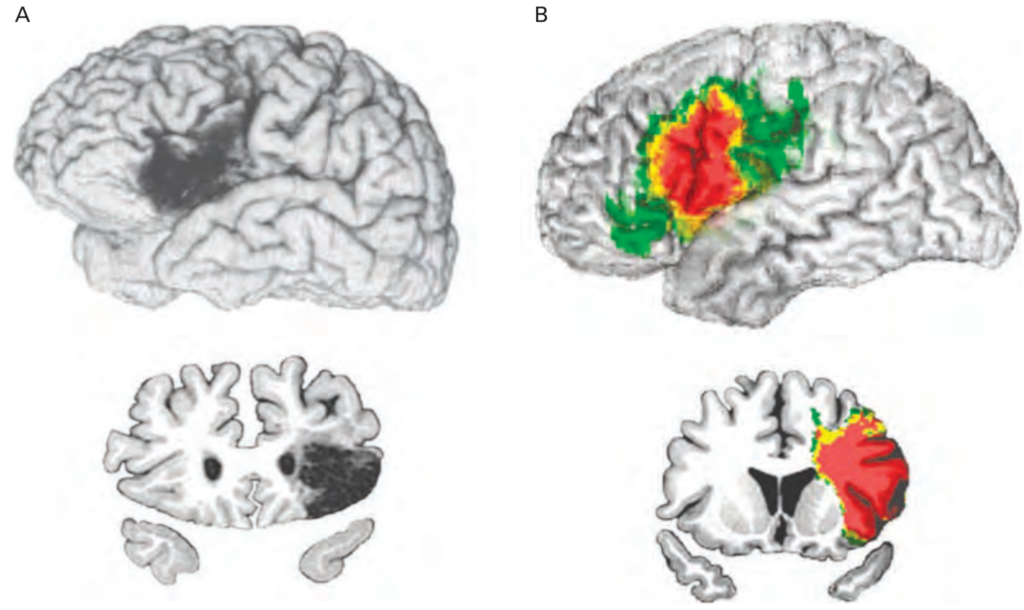


**Figure 55–6** **Sites of lesions in Broca's aphasia.** (Images used with permission of Hanna and Antonio Damasio.)

**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.

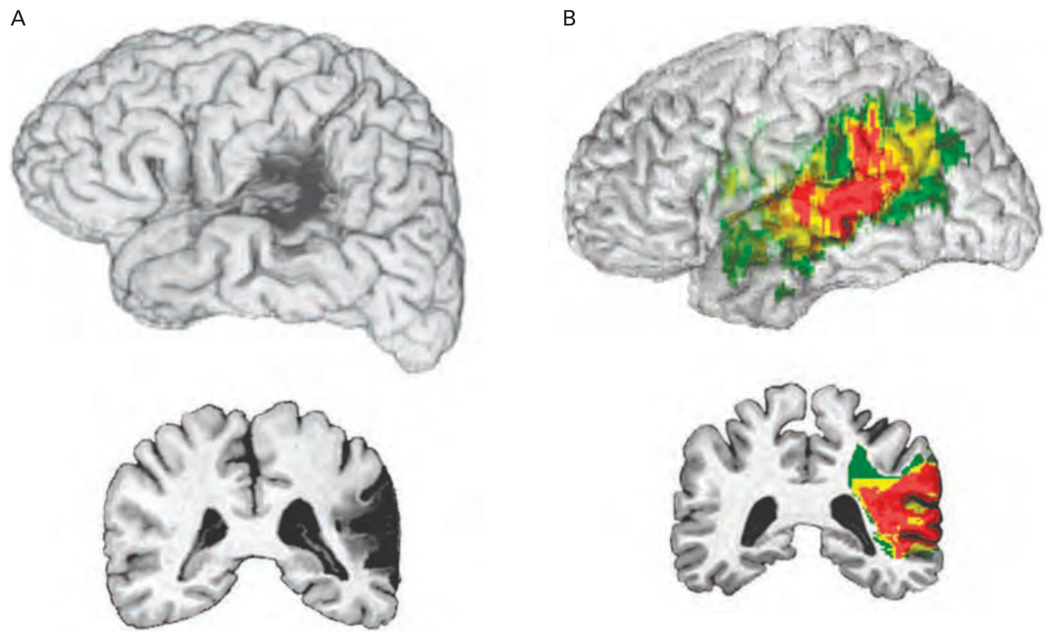


**Figure 55–7** **Sites of lesions in Wernicke's aphasia.** (Images reproduced, with permission, from Hanna and Antonio Damasio.)

**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.

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).

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

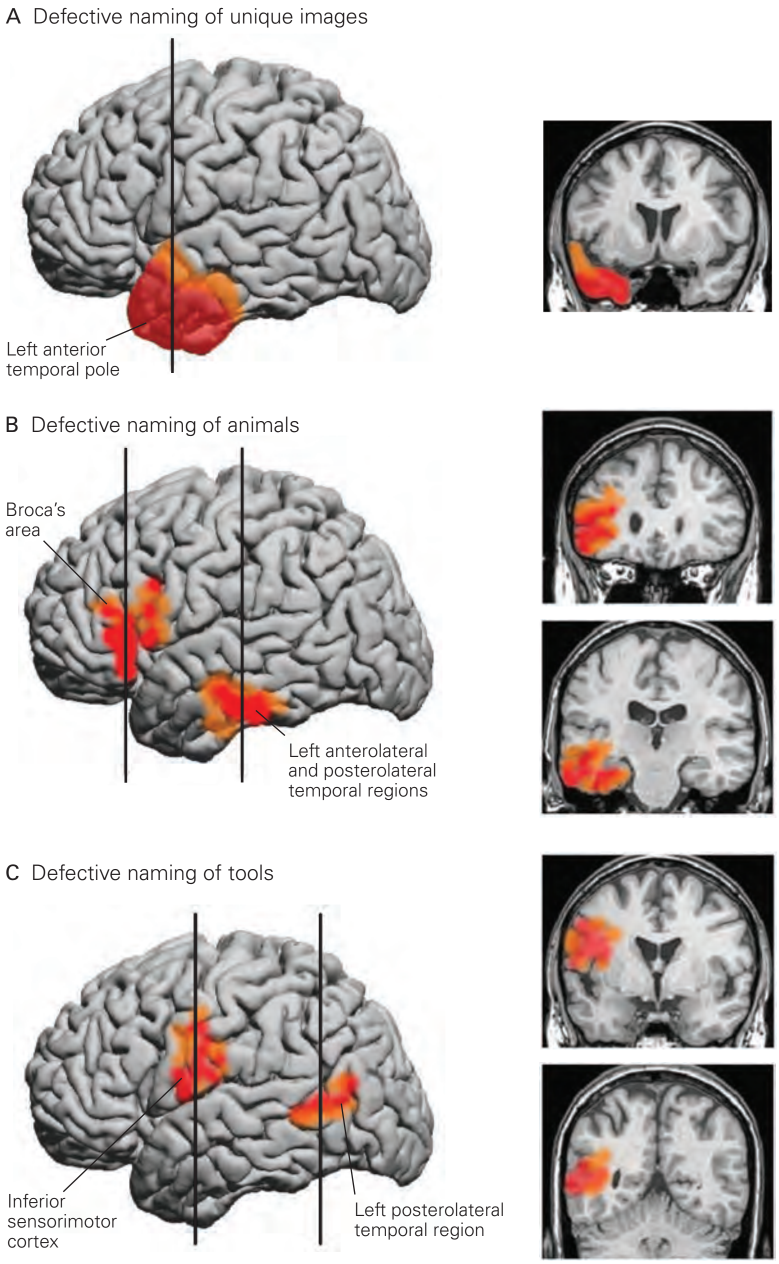


**Figure 55–8 Regions of the brain other than Broca's and Wernicke's areas involved in language processing.** Functional magnetic resonance imaging was used to study patients with selected brain lesions. (Images reproduced, with permission, from Hanna and Antonio Damasio.)

**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.

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