Chapter 3

Neurological Bases of Speech and Language

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Objectives

The brain is the only primary organ in the body concerned with processing linguistic information. The study of the manner and location of this processing is called neurolinguistics. In this chapter, you will learn about the structures and functions of the brain relative to language. When you have completed this chapter, you should be able to:

3.1 Explain the general organization and function of the cerebral nervous system.

3.2 Explain the processes of language comprehension and production.

3.3 Describe models of language processing and explain how we think humans process information.

Key Terms

After reading this chapter you should know the following important terms:

angular gyrus
arcuate fasciculus
Broca's area
central nervous system (CNS)
cerebellum
cerebrum
corpus callosum
cortex
executive function
Heschl's area
information processing
motor cortex
myelination
neurolinguistics
neuron
neuroscience
peripheral nervous system (PNS)
prefrontal cortex
reticular formation
supramarginal gyrus
synapse
thalamus
Wernicke's area
working memory

After exchanging greetings with a preschool child with whom I had been acquainted previously, he eyed me suspiciously for several seconds. When I inquired if anything was wrong, he asked, "Do I remember you?" In our study of language, we might ask our brains similar questions regarding incoming and outgoing linguistic messages and the ways in which this information is processed. And that's exactly what we're going to do in this chapter. We're going to try to describe how our brains process language.

The study of neuroscience focuses on two aspects of the nervous system:

1. Neuroanatomy, or where structures are located
2. Neurophysiology, or how the brain functions

As sciences go, neuroscience is relatively new and relies extensively on the recent advances in neural or brain imaging.

Neurolinguistics, as the name implies, is concerned with neurology and linguistics. More specifically, neurolinguistics is the study of the neuroanatomy, physiology, and biochemistry of language. Neurolinguists try to identify the structures in the nervous system involved in language processing and to explain the process.

In this chapter, we will examine the main structures of the central nervous system, specifically those involved in processing language. We will also discuss the functioning of these structures and construct a model for language processing. Finally, we'll discuss the related topic of information processing as a way to explore the how of processing.

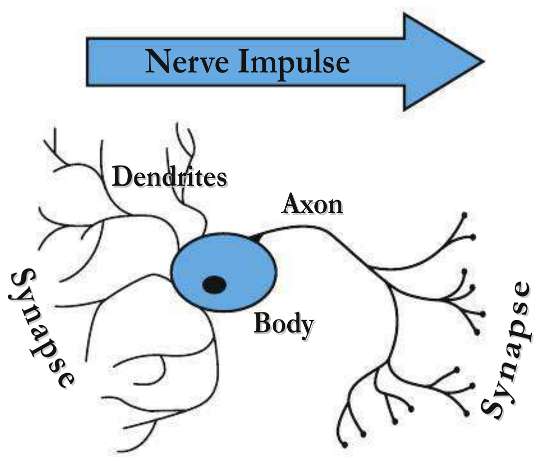
Central Nervous System

Your nervous system is complicated. Our discussion must necessarily include both human anatomy and physiology as well as the processes at work. Let's begin with the basic unit, the neuron, and work our way up.

Neurons

The neuron, or nerve cell, is the basic unit of your nervous system. A nerve is a collection of neurons. There are approximately 100 billion neurons in your nervous system. Each neuron consists of three parts: a cell body, a single long *axon* that transmits impulses away from the cell body, and several branchy *dendrites* that receive impulses from other cells and transmit them to the cell body (see Figure 3.1). Axons vary greatly in length from 1 millimeter to 1 meter. Neurons do not actually touch each other but are close enough to enable chemical-electrical impulses to "jump" the minuscule space, or synapse, between the axon of one neuron and the dendrites of the next. In short, the electrical charge of one neuron is changed by the release of neurotransmitters at its axon, which in turn affects the release of other neurotransmitters at the dendrite end of the second neuron. And it all happens instantaneously.

Figure 3.1 A Basic Neuron



Components

Your nervous system consists of your brain, spinal cord, and all associated nerves and sense organs. Your brain and spinal cord make up your central nervous system (CNS). Any neural tissue that exists outside your CNS is part of your peripheral nervous system (PNS), which conducts impulses either toward or away from your CNS. Your nervous system is responsible for monitoring your body's state by conducting messages from the senses and organs and responding to this information by conducting messages to the organs and muscles. These messages are transmitted through nerves.

Although we will concentrate on the CNS in this chapter, we should comment on the PNS before we move on. The PNS consists of 12 cranial and 31 spinal nerves that interact with the CNS. The cranial nerves are especially important for speech, language, and hearing and course between your brainstem and your face and neck.

Most of your nervous system's neurons (approximately 85%) are concentrated in the CNS. At its lower end, your CNS contains the spinal cord, which transmits impulses between your brain and the peripheral nervous system. So important is the CNS to functioning that it is encased in bone and three membranous layers called the *meninges*. At the top of the spinal cord is your brainstem, consisting of the medulla oblongata, the pons, the thalamus, and the midbrain. These structures regulate involuntary functions, such as breathing and heart rate. Within the brainstem is a compact unit of neurons called the reticular formation. This body acts as an integrator of incoming auditory, visual, tactile, and other sensory inputs and as a filter to inhibit or facilitate sensory transmission. The thalamus, also in your brainstem, relays incoming sensory information (with the exception of smell) to the appropriate portion of your brain for analysis and prepares your brain to receive input.

The cerebellum, or "little brain," located at the posterior base of your brain, consists of right and left hemispheres and a central region called the *vermis*. Although the cerebellum coordinates the control of fine, complex motor activities, maintains muscle tone, and participates in motor learning, neuroimaging indicates that the cerebellum also has considerable influence on language processing and on higher-level cognitive and emotional functions (Highnam & Bleile, 2011). The cerebellum's posterior lobe modulates this nonmotor processing, which may include the following:

- Executive functioning or the ability to manage several cognitive tasks to reach a particular objective.
- Working memory, critical for storage and manipulation of information during processing.
- Divided attention or attention to more than one stimulus or to a stimulus presented in more than one modality, such as visual and auditory.
- Modulation of affect or emotion.

Information flows from the upper portions of the brain to the cerebellum and back again in the form of feedback on the progress of the communication. In this way, the cerebellum acts as a check on communication success. Although the role of the cerebellum in the processing of language is apparent, the exact nature of this role is unknown.

CEREBRUM Atop the brainstem and the cerebellum is your cerebrum, which is also divided into left and right hemispheres. The cerebrum is the largest portion of your brain, accounting for 40% of your brain's total weight.

Application Exercise 3.1: The Nervous System

Most sensory and motor functions in the cerebrum are *contralateral*, which means that each hemisphere is concerned with the opposite side of the body. With a few exceptions, the nerves from each side of the body cross to the opposite hemisphere somewhere along their course. Two exceptions to this crossover are vision and hearing. In vision, nerves from the left visual field of each eye, rather than from the left eye, pass to the right hemisphere, and those from the right visual field pass to the left hemisphere. Hearing is predominantly contralateral but not exclusively. More on this later.

Your cerebral hemispheres are roughly symmetrical for most functions. For specialized functions, such as language, however, the hemispheres are asymmetrical, and processing is the primary responsibility of one or the other hemisphere.

Each hemisphere consists of white fibrous connective tracts covered by a gray cortex of nerve cell bodies approximately a quarter inch thick. The fiber tracts are of three types: association, projection, and transverse. Association fibers run between different areas within each hemisphere; projection fibers connect the cortex to the brainstem and below; and transverse fibers, as the name implies, connect the two hemispheres. The largest transverse tract is the corpus callosum.

Although we speak of the brain as "gray matter," the subcortical white matter is also important. For example, brain imaging indicates that children with autism spectrum disorder have more diffuse white areas of the brain that leads to differences in processing (Joseph et al., 2014).

Your cortex has a wrinkled appearance caused by little hills called gyri and valleys called fissures, or sulci. Each hemisphere is divided into four lobes labeled frontal, parietal, occipital, and temporal (Figure 3.2).

The central sulcus separates your frontal lobe from your parietal lobe. The most anterior, or forward, portion of the frontal lobe is called the prefrontal cortex, the newest portion of our brains to evolve. The prefrontal cortex is responsible for executive function, control, organization, and synthesis of sensory and motor information. Executive function tones or readies your brain and allocates resources and, as the name implies, is responsible, in part, for control over the entire operation.

Figure 3.2 Schematic Lateral Surface of the Left Cerebral Hemisphere

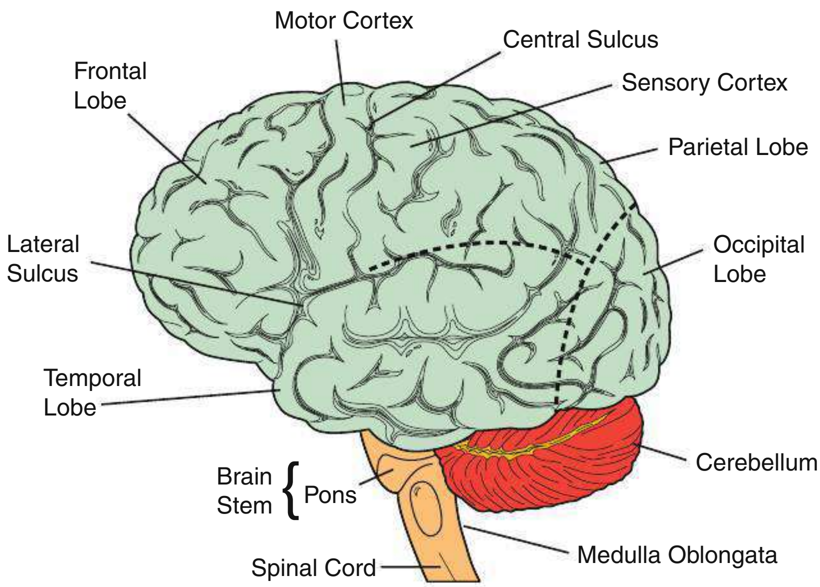
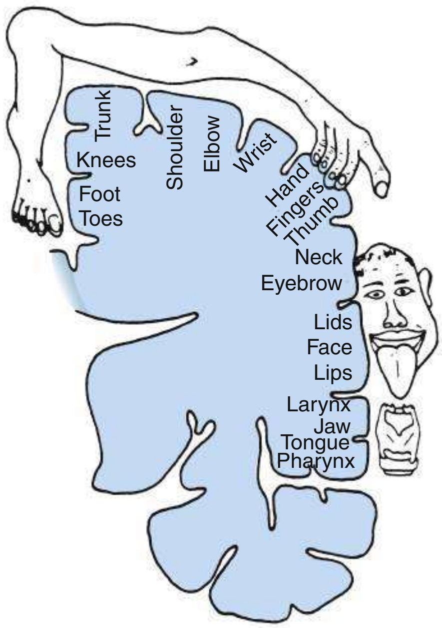


Figure 3.3 Schematic of Motor Cortex

Parts of the body drawn to represent the portion of the motor cortex devoted to each.



Large portions of your cortex serve sensory and motor functions. Immediately in front of the central sulcus is your motor cortex, a 2-centimeter-wide strip that controls motor movements. In general, the finer the movement, the larger the cortical area designated for it. In other words, your fingers have a proportionally greater cortical area devoted to motor control than does your trunk (Figure 3.3). Behind and parallel to the motor cortex and in the parietal lobe is your sensory cortex, which receives sensory input from your muscles, joints, bones, and skin. Other motor and sensory functions are found in specialized regions of your cortex. For example, the occipital lobe is primarily concerned with vision, and the temporal lobe processes auditory information.

Despite what you've just read, it would be simplistic to conceive of your brain as merely consisting of localized sensory and motor mechanisms. Instead, the integration of sensory and motor information is required for your body to function. Stated another way, your brain does not function based on separate, highly specialized areas. Rather, functions vary as portions of your brain interact with one another (Frackowiak et al., 2004). In general, the higher or more complex the brain function, the more areas involved. For example, problem solving involves more areas than bending your thumb.

Brain Functions

Three basic brain functions are regulation, processing, and formulation. The regulation function, located in the reticular formation of the brainstem, is responsible for the energy level and for the overall tone of your cortex. By maintaining the brain at a basic level of awareness and responsivity, this process aids the performance of the other two functions. The regulating process enables you to monitor, evaluate, and flexibly adjust behavior for successful performance.

The processing function, located in the posterior portion of your cortex, controls information analysis, coding, and storage. Highly specialized regions are responsible for the processing of sensory stimuli. Data from each source are combined with those from other sensory sources for analysis and synthesis.

Finally, the formulation process, located in your frontal lobe, is responsible for the formation of intentions and programs for behavior. This function serves primarily to activate the brain for regulation of attention and concentration. Motor behaviors are planned and coordinated, but not activated, within this function.

Hemispheric Asymmetry

Although there is symmetry between the hemispheres for many motor and sensory processes, the distribution of specialized functions is usually lateralized to one hemisphere. Though they possess these separate functions, the hemispheres are complementary, and information passes readily between them via the corpus callosum and other transverse bodies. Overall, neither hemisphere is dominant because each possesses specialized talents and brings different skills to a given task. Neither hemisphere is competent to analyze data and program a response alone. In fact, your brain functions as an interconnected whole with activity throughout and differing levels of response with various activities. When a specific ability and its primary processing centers are housed primarily in one hemisphere, we generally say that the hemisphere is *dominant* for that ability.

RIGHT HEMISPHERE The right hemisphere in humans is specialized for holistic processing through the simultaneous integration of information and is dominant in visuospatial processing, such as depth and orientation in space, and perception and recognition of faces, pictures, and photographs. In addition, the right hemisphere is capable of recognition of printed words but has difficulty decoding information using grapheme–phoneme (letter–sound) correspondence rules. (We'll discuss reading in more detail in Chapter 11.) Other right hemisphere language-related skills include

- comprehension and production of speech prosody and affect,
- comprehension and production of metaphorical language and semantics, and
- comprehension of complex linguistic and ideational material and of environmental sounds.

Environmental sounds include nonspeech sounds, music, melodies, tones, laughter, clicks, and buzzes. Interestingly, individuals who sign, whether deaf or hearing, have better memory for faces and objects than individuals who do not sign, suggesting that at least the visuospatial aspects of sign may also be associated with your right hemisphere.

In addition, your right hemisphere may play a role in some aspects of pragmatics, including the perception and expression of emotion in language; the ability to understand jokes, irony, and figurative language (i.e., *He hit the roof* or *I could eat an ox*); and the ability to produce and comprehend coherent discourse. These aspects of language processing are especially difficult for adults with right-hemisphere injury.

LEFT HEMISPHERE In almost all humans, the left hemisphere is specialized for language in all modalities (oral, visual, and written), linear order perception, arithmetic calculations, and logical reasoning. Whereas your right hemisphere engages in holistic interpretation, your left is best at step-by-step processing. As such, your left hemisphere is adept at perceiving rapidly changing sequential information, such as the acoustic characteristics of phonemes in speech. Processing these phonemes for meaning, however, involves both hemispheres. Studies using functional magnetic resonance imaging (fMRI) have shown a strong left hemispheric language dominance for auditory comprehension in children as young as 7 years of age (Balsamo et al., 2002).

It's important to note that this predisposed specialization requires input, primarily speech. Early language development greatly influences the development of the left hemisphere's specialization.

VARIATION Not all human brains are organized as described. In general, almost all right-handers and approximately 60% of left-handers are left-hemisphere dominant for language. The remainder of left-handers, approximately 2% of the human population, are right-hemisphere dominant for language. Thus, approximately 98% of humans are left-dominant for language.

Timing may be important. It's worth noting that infants who have consistent right-handedness established by 6 to 14 months have advanced language as toddlers (Nelson, Campbell, & Michel, 2014). Infants who establish lateralization as toddlers, whether left- or right-handedness, seem to have typical language.

A minuscule percentage of humans display bilateral linguistic performance, with no apparent dominant hemisphere. Women seem to be less strongly left-dominant than men, having a slightly more even distribution between the hemispheres. In reality, lateralization is probably a matter of degree rather than the all-or-nothing patterns suggested.

Brain Maturation

Language development is highly correlated with brain maturation and specialization. Whether this relationship is based on maturation of specific structures or on the development of particular cognitive abilities is unknown. (In Chapter 4 we'll discuss cognitive growth in the infant.) Two important aspects of brain maturation are weight and organization.

Gross brain weight changes most rapidly during the first two years of life, when the original weight of the brain at birth triples. Average brain weights are presented in Table 3.1. In addition, chemical changes occur and internal pathways become organized, connecting various portions of the brain. By age 12, the brain has usually reached its fully mature weight. The number of neurons does not change appreciably, but they increase in size as dendrites and axons grow to form a dense interconnected web. Disease, malnutrition, or sensory deprivation can result in less density and decreased functioning.

Table 3.1 Gross Brain Weight of Children

Age	Weight (grams)	Percentage of adult brain weight
Birth	335	25
6 months	660	50
12 months	925	70
24 months	1,065	80
5 years	1,180	90
12 years	1,320	100

Source: Information from Love, R., & Webb, W. (1986). Neurology for the speech-language pathologist. Boston, MA: Butterworth's.

Neurolinguistics is a specialized study of language and the brain. **Video Example 3.1: Your Brain on Language: Is Grammar Inside My Head?** provides a quick review of the relationship of neurology and linguistics.
Source: http://www.youtube.com/watch?v=aUFdUiJXS4E

Self-Check 3.1

Most of the increase in functioning is the result of myelination, or the process of sheathing of the nervous system. In general, the myelin areas are the most fully developed and those with the most rapid transmission of neural information. Myelination is controlled, in part, by sex-related hormones, especially estrogen, which enhances the process. This fact may account for the more rapid early neurological development of girls. In general, sensory and motor tracts undergo myelination before higher-functioning areas, such as those for processing language.

The brain is not simply growing. Microscopic "connections" are being made. Genes determine the basic wiring, and approximately half of the 80,000 genes in your cells are involved in the formation and operation of the CNS. It is experience, however, that determines the pathways. In the first month of life, firings across synapses may increase fiftyfold to more than one thousand trillion. Use of these neural pathways stimulates and strengthens them, making subsequent use more efficient.

Through brain use underlying functional networks are formed, organized and reorganized as children mature, some networks lateralize to the dominant hemisphere while others become bilateral or nondominant (Vannest, Karunanayaka, Schmithorst, Szaflarski, & Holland, 2009).

Language Processing

It is extremely difficult to identify the exact spot where language and speech reside in your brain. Processing areas often overlap. We are on safer ground to state that language is a complex process performed by many different interconnected networks in your brain rather than a single area.

Recent advances in brain imaging have enabled researchers to monitor cerebral blood flow while a subject is conducting specific linguistic tasks. Such online or "real-time" studies have helped researchers confirm that linguistic processing, such as word

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Neurological impairment may require that a person find other means of communication.

retrieval and word and sentence comprehension, often relies on contributions from differing areas of your brain. As a result, brain imagery results have fostered a theoretical move away from processing models based on exclusive sensory input and motor output channels of language processing to an integrated model (Friston, 2002).

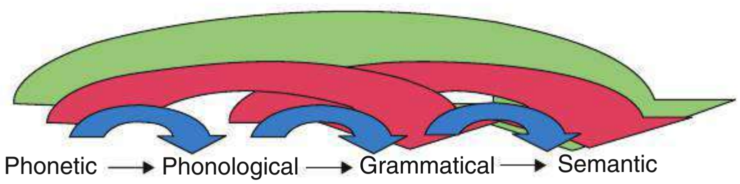
Position emission tomography (PET), a brain-imaging technique, has identified several regions of the brain that are active during speech-sound processing. Although there is greater activation in the left hemisphere during both perception and production, some right-hemisphere involvement also occurs. In general, the frontal and temporal lobes are also more active than other regions in both perception and production, but there is no evidence for a single processing center. Even areas of the frontal lobe important for speech production are not speech-specific but also participate in nonspeech tasks.

In the 1960s and 1970s, many linguists assumed that language comprehension and production were linear in nature, with processing proceeding in a sequential fashion. For example, comprehension was assumed to flow as follows:

phonetic ⟶ phonological ⟶ grammatical ⟶ semantic

Production ran in the opposite direction. It does seem plausible that words would be selected independently of sentence frames and then put together like cars in a train. But this is not the case.

A more accurate representation of the comprehension process is more complex and would look more like the following:



All areas contribute as information becomes available and seemingly earlier or later stages are, in fact, not so. For example, context can penetrate the earliest stages of word identification in comprehension, and speech sounds can affect sentence formation in production.

Linguistic processing, both comprehension and production, depends on your lexicon, or personal dictionary, of stored words and high usage phrases and on your stored linguistic rules. The systems for comprehension and production overlap partially. Brain-imaging techniques indicate that the posterior temporal lobe in the left hemisphere is associated with both comprehension and production (Hickok, 2001).

In all honesty, we're still not sure if comprehension and production are a single, integrated skill or separate processes that draw on shared knowledge of language. This question is complicated by the nature of much language processing that occurs in real time with little obvious pre-thought. Some have argued that even language learning occurs in the moment and consists of learning the process of language use rather than learning abstract symbols and rules (Chater Stewart, McCauley Morten, & Christiansen, 2016).

Many parts of your brain are active in language processing. In addition, the number and location of these activated regions differ across individuals and vary with the task based on the type of input and output, amount and kind of memory required, the relative level of difficulty and familiarity, attentional demands, and competition from other tasks. Although there is little evidence of a unitary language-processing area, some areas do seem to be more important than others, especially the frontal and temporal regions of the left hemisphere.

Language Comprehension

Comprehension consists of auditory processing and language decoding and involves many areas of your brain working together. Auditory processing is concerned with the nature of the incoming auditory signal, whereas decoding considers representational meaning and underlying concepts. Processing begins with attending to incoming stimuli. Because it has a limited capacity to process incoming data, your brain must allocate this capacity by focusing its attention on certain stimuli while ignoring or inhibiting others. Think about what happens when you attend to someone talking to you while a TV is blaring in the background.

LOCATION Auditory signals received in your brainstem are relayed to an area of each auditory cortex called Heschl's area (or gyrus). As shown in Figure 3.4, 60% of the signal is received at Heschl's area from the ear on the opposite side of your body. Heschl's area and the surrounding auditory areas separate the incoming information, differentiating significant linguistic information from nonsignificant noise. Linguistic information receives further processing. Linguistic input is sent to your left temporal lobe for processing, while paralinguistic input (intonation, stress, rhythm, rate) is directed to your right temporal lobe. Initial phonological analysis begins in Heschl's area and continues further along in the process (Frackowiak et al., 2004). Figure 3.5 presents receptive linguistic processing.

Although linguistic analysis is nearly instantaneous, long units such as sentences require the aid of memory in which the incoming information is held while analysis is accomplished. Called auditory working memory, it is most likely located in or near Broca's area in your left frontal lobe (Caplan, 2001; Fiebach, Schlesewsky, & Friedrici, 2001;

Figure 3.4 Following the Path of Receptive Processing