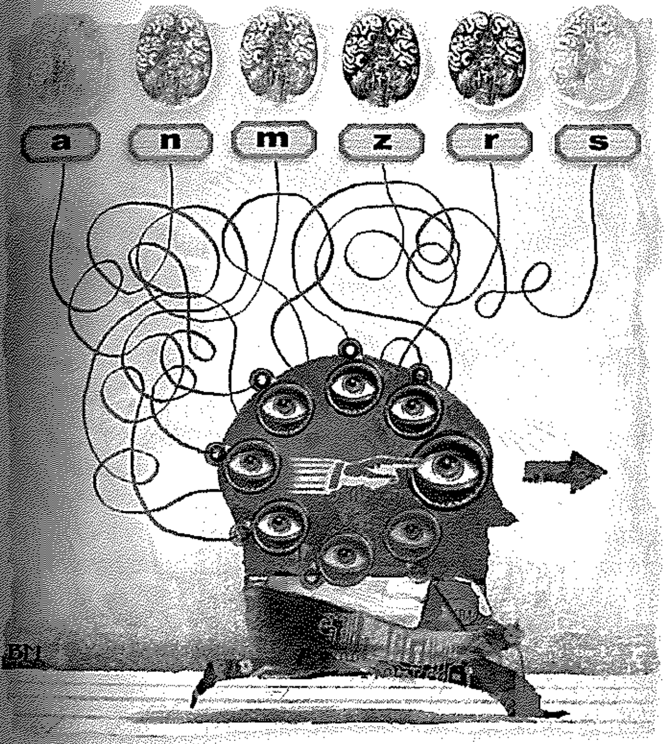
# 3

# Language and the Brain



Maybe you were the sort of kid who liked to take things apart to see how they work. If so, you know just how informative it could be to pry the cover off a watch or a clock radio or even a car engine to inspect its mechanical guts. No doubt, a similar curiosity drove the early anatomists of the seventeenth and eighteenth centuries as they peeled back skin to see how the human body is put together (see **Figure 3.1**). Being able to look at the physical systems inside the body yielded many groundbreaking insights—such as the realization that blood doesn't slosh around or seep from one part of the body to another, but circulates throughout the body in special-purpose channels.

Among language scientists, I always think of **neurolinguists**—those who study how the physical brain relates to language behavior—as grown-up versions of the kids who liked to take things apart to see how they work. But the researchers who have chosen this field as their life's work need a heavy dose of patience along with their curiosity, because the brain has been much less amenable to giving up its mechanical mysteries than a car engine or the human digestive tract.

One reason for the brain's inscrutability is that it's not made up of clearly separable parts that are linked together, unlike a car engine or much of the human body. It's easy to intuit that the stomach and lungs are likely to have very different functions: they're quite obviously independent organs made of different kinds of tissue, connected to different "other parts." It's much harder to pull the brain apart into its components. It's essentially a lump of dense tissue weighing about 1.3 kg (3 pounds) made up of interconnected neural cells (approaching

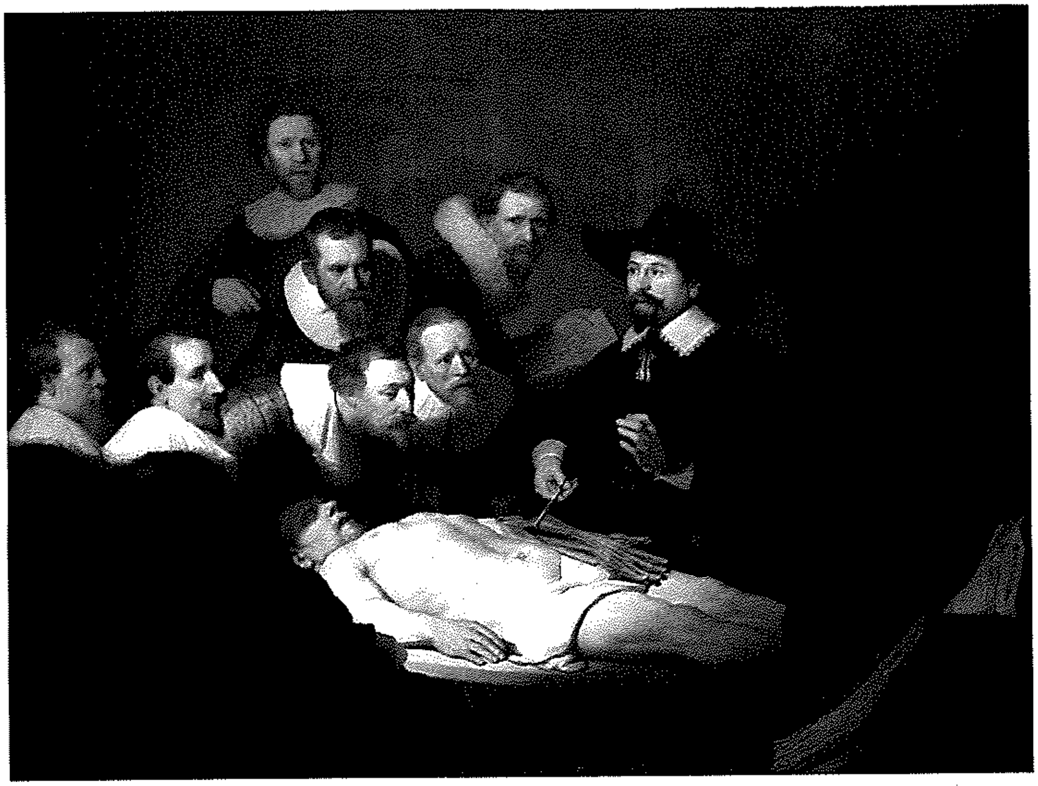


**Figure 3.1** Rembrandt's *The Anatomy Lesson of Dr. Nicolaes Tulp*, painted in 1632, depicts an anatomy demonstration of that time. Such lessons were open to the public for a fee.

100 billion of them). Some clues can be gleaned from the more obvious physical structure of the brain. For example, the left and right hemispheres are largely physically separate from each other, so it seems reasonable to ask whether the two sides *do* different things. More subtle clues can be discerned by looking at brain tissue under a microscope; if two different regions of the brain have a different cellular makeup, this suggests that they may take on somewhat different tasks. But even today, the connection between the structure of brain tissue and the functions those tissues serve is far from clear. The brain poses significant challenges simply because it's a physical object whose function is not easily understood from its anatomical form. This fact is a big reason why an understanding of the brain has historically lagged far behind our understanding of the other organs in the human body.

A second and even greater difficulty comes from the sheer number, variety, and complexity of the brain's functions. In order to understand how a physical object "works," you need to have a clear idea of what it does. Sometimes this is trivially easy; for example, the function of a (non-digital) clock is to move the clock's hands around in a way that is consistently linked to units of time. When you look at the wheels and gears inside of a clock, it's with the aim of understanding how it accomplishes this specific function. A car is a bit more complicated. Sure, its ultimate purpose is to "drive," but peering under the hood is going to be a lot more informative if you've first been able to break down that larger purpose into component tasks. It helps to start with the idea that a number of different sub-tasks are involved, with the expectation that these map onto different mechanical "systems." For example, in order to "drive," your car's engine has to be able to start, the wheels have to turn in specific directions, the vehicle has to move forward *and* backward while transforming fuel into energy, the speed has to be modulated, and the car needs to be able to be brought to a stop—to name just a few sub-tasks. The different systems that accomplish

**neurolinguists** Scientists who study how the physical brain relates to language behavior.

these tasks all operate somewhat independently of each other, but their actions need to be coordinated with one other.

Needless to say, the brain is massively more complicated than a car. Among its various tasks are, to name only a very few: regulating your breathing and heartbeat, keeping food moving through your digestive system, recognizing someone familiar, recognizing a dangerous situation, and operating your muscles while you walk or play the piano. Your brain also gives you the ability to solve quadratic equations, learn to dance the tango, evaluate a political argument, navigate unfamiliar city streets, decide whether to post those photos online, and, oh yes, use language to communicate. The brain has a staggering range of functions, some of which possibly overlap, and some of which almost certainly don't. For any given task—say, using language—there's still a lot of uncertainty about the relevant sub-tasks that might form different "systems." For example, is combining sounds part of the same system as combining words into sentences? Is combining words in simple sentence structures part of the same system as creating more complex, recursive structures? Is understanding the meanings of words that you hear part of the same system as choosing specific words to convey the meaning you intend? Good luck trying to find a language scientist who will confidently answer all of these questions—and if you do, good luck finding a second one who agrees with the first. And, given that the physical structure of the brain doesn't make it glaringly obvious how many systems it's divided up into, neurolinguists have to rely especially heavily on reasonable hypotheses about what these separate systems might be.

In short, then, what we *don't* know about language and the brain far outweighs what we *do* know. At the same time, it's hard to imagine that we can ever deeply know how language "works" without having a good sense of how it's implemented in the brain. In the spirit of all those who've ever dismantled stuff to see how it operates, this chapter follows the often ingenious attempts of researchers to figure out how the physical brain accomplishes the mysterious task of language.

## 3.1 What Can Genetic Disorders Tell Us about Brain Systems?

### *Brain systems and behavioral syndromes*

As I've suggested, before we start peering beneath the skull at neural matter itself, it would be helpful to have some preliminary good ideas about how the brain might be organized into separate systems. This would constrain our guesses about how the brain's matter is laid out. For example, if certain behaviors group together as part of an integral system, we might look for evidence that those tasks are implemented in a common brain region, or that they're accomplished by similar kinds of neural tissue, or that the regions responsible for them are physically connected in some way.

What clues do we look for in trying to isolate separate systems? One approach is to look closely at *disorders of thought and behavior that have a genetic origin*. A number of genetically linked conditions affect cognitive skills. In surveying these conditions, it quickly becomes apparent that brain functions can be targeted in selective ways, leading to different categories of linked impairments, or **syndromes**, rather than just an overall reduction in cognitive abilities.

**syndrome** Literally, "occurring together" (Greek *syndromos*). A group of symptoms that collectively characterize a medical or psychological disorder or condition. The presence of a syndrome can lead to the identification of a genetic basis for the condition.

Ever since Down syndrome was definitively linked to a chromosomal anomaly in 1950, we've known that the ability to learn and carry out intellectual tasks can be disrupted by genetic "glitches." Since then, scientists have identified a variety of learning and psychiatric disorders that have a strong genetic

**double dissociation** In reference to language studies, the simultaneous existence of a situation in which language is impaired but other cognitive skills are normal, or a situation in which language is normal despite the impairment of other cognitive functions.

**Williams syndrome (WMS)** Genetic syndrome, of particular interest to language researchers, in which language function appears to be relatively preserved despite more serious impairments in other areas of cognitive function.

basis. Given that specific, identifiable genetic anomalies can lead to very distinctive patterns of behavior, it's likely that the genes involved have a direct impact on the neural structures that underlie the behavior. Hence, by looking at a variety of disorders and seeing which behaviors are affected and which behaviors remain normal, we can generate some reasonable hypotheses about the underlying brain machinery.

Let's start by considering whether there really is such a thing as a language system in the brain. In Chapter 2, you were introduced to a debate over whether there's a separate, dedicated language system that has evolved in humans over time, or whether language has emerged as a by-product of humans' generally muscular intelligence. These two perspectives fuel very different expectations about how closely linked language functions should be with other aspects of intelligence. If language is an outgrowth of overall intellectual ability, then genetic anomalies that curtail intelligence should have a dramatic effect on language. On the other hand, if language is a specially evolved "module" (much like a specialized organ), it might not be that tightly connected to other cognitive skills. In fact, the most compelling evidence of a separate language module or brain system would be to find a **double dissociation** between language and other cognitive skills: that is, a situation in which language is impaired but other cognitive skills are normal, and, on the flip side, a situation in which language works just fine despite the impairment of other cognitive functions. Double dissociation would provide strong support for the notion that language and cognition rely at least in part on separable neural systems.

### *Williams syndrome*

**Williams syndrome (WMS)** has attracted the attention of language researchers because it appears to be a case where language function is fairly well preserved despite some striking impairments in other domains. Williams syndrome is caused by a specific genetic anomaly on chromosome 7. Together with certain facial features and cardiovascular problems, it usually results in learning disability, with the overall IQs of affected individuals typically falling in the 50–70 range. People with WMS tend to be socially gregarious and, as it turns out, are often very verbal. Several language researchers have been struck by this last trait, especially given the tremendous difficulties that people with WMS often show on a variety of cognitive tasks, including those that rely on numerical or visual–spatial skills.

Ursula Bellugi and her colleagues (2000) have documented the linguistic and non-linguistic skills of people with Williams syndrome in comparison to the cognitive profiles of people with Down syndrome, another genetic anomaly that leads to intellectual impairments. When Bellugi compared a group of adolescents with WMS and a group with Down syndrome, she found that the overall scores on tests for IQ and cognitive functioning were similar for the two groups. In particular, the WMS group showed quite dramatic difficulties with numerical concepts—for example, many of them said they would rather have "50 pennies" than "5 dollars," and when asked to estimate the length of a bus, they gave responses such as "3 inches or 100 inches maybe" and "2 inches, 10 feet." Needless to say, they had a great deal of trouble carrying out tasks like making change, balancing a checkbook, or cooking from a recipe. Some of their most dramatic difficulties were in spatially organizing parts of objects into coherent wholes.

Typically, individuals with Williams syndrome operate at about the level of an average 6-year-old when it comes to their conceptual understanding, but their conceptual weaknesses are often accompanied by very adult-sounding language. For instance, one young woman, who was literate and enjoyed reading about vampires, seemed to have trouble understanding the concept of vampires; when asked to define one, she offered that a vampire is "a man who climbs into ladies' bedrooms at night and sinks his teeth into their necks." When asked why vampires behave in this way, she said "vampires must have an inordinate fondness for necks" (Johnson & Carey, 1998).

In Bellugi's comparison of Williams and Down syndromes, language was clearly more sophisticated among the Williams group. Their sentences were more fluent and complex, and they showed a stronger understanding of how syntactic structure contributes to meaning. For example, in a sentence like *The man is chased by the horse,* you need a good grasp of syntax in order to know who is doing the chasing and who is being chased—you can't simply deduce this from the words *man, chased,* and *horse.* Individuals with Down syndrome performed almost randomly with such sentences when matching them up with pictures of the events they depicted, while the Williams group showed much better performance. Examples of the divergent strengths and weaknesses of the two groups are shown in **Box 3.1**.

Some language scientists have taken results such as Bellugi's to be strong evidence for a genetically specified language module that is independent of overall intelligence. But a good amount of subsequent research has challenged this conclusion.

First of all, comparing individuals with Williams syndrome against a group of people with Down syndrome doesn't necessarily provide the best assessment of their linguistic strengths, even if both groups are matched for overall IQ. A slightly different picture emerges when people with Williams syndrome are compared with typically developing kids of the same **mental age**—that is, a group of children who are at the same overall level of cognitive functioning. The logic is that if a person with Williams syndrome is at the cognitive level of a 6-year-old, then it makes sense to compare his language abilities with those of a typical 6-year-old. If these abilities are at about the same level, this suggests that the linguistic abilities of the person with Williams are closely linked to his other cognitive abilities. In order to conclude that the language module is preserved in Williams syndrome, we'd need to see evidence that language abilities actually *exceed* what we'd expect to find based on mental age alone (and perhaps are closer to that person's chronological age).

**mental age** A person's overall level of cognitive functioning, related to the chronological age of a person with typical development.

In fact, on most detailed measures of language, subjects with Williams syndrome perform about as well as you'd expect based on their mental age (for a review, see Brock, 2007). The truth is, a typical 6-year-old has pretty good language skills too. The striking—but somewhat misleading—impression that a number of researchers had of the unexpectedly strong linguistic performance of the WMS individuals exemplified in Box 3.1 probably came about for several reasons: (1) when they are compared with subjects with Down syndrome, their language *is* good, but this is largely because Down subjects *under*perform on language relative to their mental age (a fact which, in and of itself, demands an explanation and suggests that language and cognitive abilities aren't always in sync); (2) the language abilities of WMS individuals are strikingly good when compared with their difficulties with visual–spatial and numerical tasks—but this is because performance on these latter tasks is much *worse* than you'd expect based on their mental age; and (3) certain superficial features of WMS language (such as the use of rare words or unusual turns of phrases) give the impression of greater linguistic sophistication, but these words and phrases may be used without full control or understanding.

So, a closer look at the cognitive and linguistic profiles of people with WMS doesn't really show a dramatic dissociation between language and overall cognitive ability. At the same time, results from a wide variety of language mea-

### BOX 3.1

## Linguistic and non-linguistic impairments in Williams and Down syndromes

Ursula Bellugi and her colleagues (2000) compared a group of adolescents with Williams syndrome (WMS) and a group with Down syndrome (DNS). All the subjects in these comparisons had approximately equivalent overall IQ scores.

**Linguistic performance**

*Hypothetical questions containing conditional structures.* WMS subjects often responded with very adult-sounding language.

Experimenter: "What if you were a bird?"

WMS 1: "You could fly, you could have babies, fly north or south, east or west."

DNS 1: "Bird seeds."

WMS 2: "Good question. I'd fly through the air being free."

DNS 2: "You'd be strong."

WMS 3: "I would fly where my parents could never find me. Birds want to be independent."

DNS 3: "I not a bird, you have wing."

*Definitions of homonyms.* WMS subjects frequently were able to provide both meanings, while DNS subjects typically reported only one.

Experimenter: "What does ***nuts*** mean?"

WMS: "There are two kinds of nuts, peanuts and nuts and bolts."

DNS: "We crack nuts. We eat nuts."

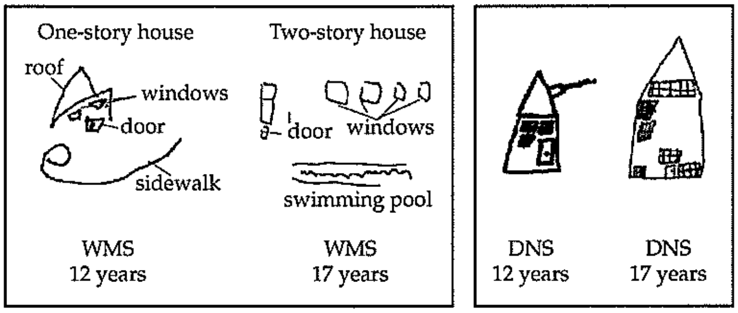
Experimenter: "What does ***club*** mean?"

WMS: "A secret kind of club, and a club with spurs—those pointy things for killing animals."

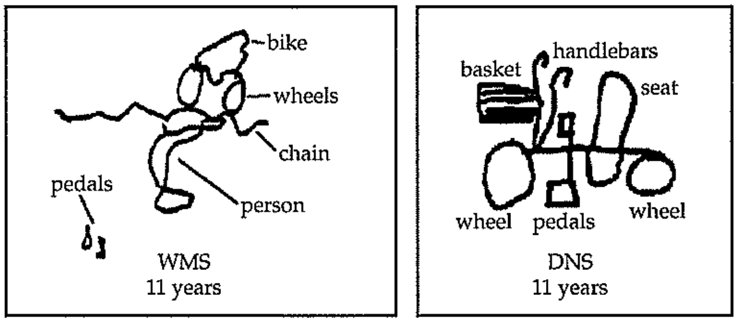
DNS: "Go to a club. I'm in the key club."

**Non-linguistic (visual-spatial) performance**

*Performance on drawings of common objects.* WMS subjects demonstrated significant difficulty with visual-spatial representation. (Drawings from Bellugi et al., 2000.)



Drawings of a house by subjects with Williams and Down syndromes.



Drawings of a bicycle by subjects with Williams and Down syndromes.

sures *do* suggest a couple of areas of strength for WMS subjects. Relative to their mental age, they score especially well on tests of receptive vocabulary (words that are recognized and understood) and the ability to hold auditory material in short-term memory. Relative weaknesses within the language domain also exist, however; for instance, WS subjects have been found to score poorly on comprehension of complex syntactic structures (e.g., Mervis, 1999).

The research is far from complete, and there are ongoing questions about the most appropriate comparisons to draw across populations (see **Method 3.1**), but the emerging message is this: Williams syndrome doesn't appear to supply

## METHOD 3.1

### Drawing comparisons across populations

Looking in detail at the cognitive profiles of people within atypical populations (such as individuals with Williams or Down syndrome) can provide a great deal of insight about which types of cognitive abilities tend to cluster together, and which can develop separately from each other. But what are the best comparisons to make between different populations in order to get an accurate picture of which abilities are "normal" and which are not? What characteristics should our sample populations have? If we were simply to compare a random group of people with Williams syndrome and a random group of people without Williams syndrome, we might inadvertently end up with two groups whose members were very different in their average age, their range of experiences, how much time they'd spent acquiring certain skills, and so on. In fact two random populations can be so different in so many ways that it can be hard to draw useful conclusions from their differences. To avoid this pitfall, researchers make an effort to match certain characteristics across populations. But there are a number of different ways in which different populations might be matched. What's the best approach?

One choice might be to align populations by overall IQ and then compare the two groups on specific skills to see if there are uneven patterns. If there are differences across groups, it certainly suggests that some skills aren't predicated on overall intelligence alone. But, as we've seen with the comparisons of Williams and Down subjects in Box 3.1, it can be hard to draw firm conclusions about whether specific skills are within the normal range or not, and hence whether we can consider them to be "spared" abilities. Showing that people with Williams have stronger linguistic abilities than people with Down syndrome, for example, doesn't allow us to conclude that language is normal for the Williams group, since it could simply be the case that language abilities are especially deeply impaired in the Down comparison group.

For this reason, many researchers prefer to compare a group of atypical individuals against those who are developing typically, and align the two groups by mental age, that is, the age at which typically developing children would achieve the same IQ score as those in the contrasting population. But matching on this variable can introduce its own set of problems. If there's a big discrepancy between mental age and chronological age, this leads to very young typical children being compared with older atypical individuals. But such a big gap in age can lead to quite big differences in sociability, attention span, comfort level around strangers, motivation, willingness to participate in a test situation, or various other factors that might affect how the subjects actually perform on the tests that they're faced with. Or, the older group may have had time to develop strategies for compensating for their deficits, which might make their abilities look more intact than they really are. Moreover, matching by mental age means that there's a lot of weight placed on the accuracy of the tests that are used to assess mental age. If the tests turn out to be less accurate or appropriate for use with certain populations, this compromises the whole matching paradigm.

Sometimes, a comparison based on general evaluations of intelligence might be too blunt an instrument, especially if we're interested in looking in more detail at whether there are uneven profiles of performance within the domain of linguistic abilities. In that case, researchers might choose to match the subject groups on some measure of language ability. For instance, they might be matched on vocabulary size, as measured by the Peabody Picture Vocabulary Test, in which children are asked to match a word spoken by the experimenter with one of four available pictures. Or the groups might be matched on the measure of mean length of utterance, which provides a count of the average number of distinct word-like units that the subject produces in a sentence (and which increases quite rapidly with age, especially in the first few years of language learning). This allows the researchers to assess whether, even when a single coarse measure of language development is held constant, there are peaks and valleys in linguistic abilities.

Ultimately, there's no single perfect matching criterion, and the choices researchers make often reflect (1) the nature of the populations that are being tested, and (2) the questions of interest. Sometimes more than one matching group is tested, in order to provide more than one perspective on the relevant comparisons. But when you read papers in which conclusions are made based on comparing two groups, it's always worthwhile to take a close look at the groups that were tested and how they were matched. Were the two groups really equivalent along the most important dimensions, and did the choice of matching criteria support the conclusions that were drawn? How might the results have been affected if a different comparison group had been chosen?

definitive evidence for an independent language module, but it does point to an intriguing separation of some specific cognitive skills, both linguistic and non-linguistic in nature. The hope is that by systematically studying many of the skills that are involved in learning and using language, researchers will ultimately come to a better understanding of the particular skills that have a genetic basis, and the consequences for language when these skills are disrupted.

**specific language impairment (SLI)** A disorder in which children fail to develop language normally even though there are no apparent neurological damages or disorders, no general cognitive impairment or delay, no hearing loss, and no abnormal home environment that would explain this failure.

## *Specific language impairment*

Having asked whether Williams syndrome is truly a disorder in which language is preserved while other cognitive functions are deeply affected, we will now look at the flip side of the same question: Is there a disorder in which language is selectively disrupted while other cognitive functions are normal? A number of researchers have argued that there is such a condition.

**Specific language impairment (SLI)** is defined as a disorder in which children fail to develop language normally even though there's no obvious reason for this—that is, no apparent neurological damage or disorders, no general cognitive impairment or delay, no hearing loss, and no abnormal home environment. Children with SLI usually start speaking later than their peers, and once they do talk, their language shows evidence of odd glitches, some of which linger into adulthood. They produce strangely ungrammatical sentences (for example, *Who did Marge see someone?* and *Yesterday I fall over*), and they persist in such errors well past the age when children normally make elementary syntax errors. Abnormalities at all levels of language structure have been found—that is, at the levels of sound structure, sentence structure, and the structure of complex words. (See **Table 3.1** for a more detailed description and examples of language deficits found in SLI.)

**TABLE 3.1 Common linguistic and non-linguistic deficits in specific language impairment (SLI)**

**Linguistic deficits**

*Deficits of sound,* including:

- difficulty in producing words with complex consonant clusters like *spectacle* or *prescription*
- trouble in perceiving subtle distinctions among speech sounds
- trouble analyzing the sound structure of words and sound sequences; e.g., difficulty answering questions such as, "In the word *spray*, what sound follows 'p'?"

*Words:* difficulty in tagging words with the right grammatical markers for plural, tense, etc., especially with new words; e.g., difficulty in filling in the blanks for questions like "This is a wug. Now there are two of them: there are two ____."

*Sentence structure:* trouble understanding the meaning of sentences with multiple participants or complex sentence structure, e.g., *Frank introduced Harry to Sally; Harry was kissed by Sally.*

**Non-linguistic deficits**

*Perception of rapid stimuli:* trouble perceiving rapid sequences of sounds or images

*Working memory:* short memory spans for both speech and non-speech stimuli

*Analogical reasoning:* impaired reasoning by analogy, even in tasks that don't rely heavily on language

*Visual imagery:* difficulty in performing tasks that require mentally rotating objects and imagining what they would look like from a different perspective

Adapted from Joanisse and Seidenberg, 1998.

Unlike Williams syndrome, no single genetic anomaly has been identified as being at the root of SLI. But there's quite strong evidence that the disorder has a hereditary component, as gleaned from family histories and studies of identical and non-identical twins, and from the fact that a number of genetic anomalies have been found in people with SLI.

By virtue of its clinical definition and its very name, specific language impairment seems to offer evidence of language as a separate system that develops in the brain—or at the very least, evidence that certain aspects of language structure behave as modules that are independent of other cognitive functions, and that have a direct basis in genetics. This is the point of view taken by researchers such as Heather van der Lely and Ken Wexler (e.g., van der Lely & Marshall, 2011; Rice & Wexler, 1996). These researchers disagree with each other on the details, but their general approach is to say that SLI is due to a genetically based disruption in the process of learning language structure. The end result is a "broken" grammar, or being stuck at a stage of arrested development in the learning of complex language structure. In short, they take a **domain-specific perspective** on SLI, in which the linguistic deficit strikes at mechanisms that are particular to language, rather than ones that are shared with other cognitive abilities.

But, as you might have guessed from our discussion of Williams syndrome, the picture is less clear close up than it appears from a distance. For starters, the dissociation between language and other cognitive functions in SLI is far from sharp. It's certainly true that the problems that usually bring children with SLI into clinicians' offices are their difficulties with language, rather than any other obvious signs of cognitive delay or impairment; in other aspects of their lives, these kids seem to be functioning fine. But more detailed testing shows that many children with SLI also show unusual performance on other tasks that are at best indirectly related to language structure (see Table 3.1). Basic speech perception is often impaired, with SLI kids having more trouble distinguishing between similar sounds like "ba" and "pa." They might also have shorter memory spans, as measured by their ability to retain words or other units in memory over a short period of time. Some children also have trouble with control over their articulatory systems, or even with more general aspects of motor coordination. (See Joanisse and Seidenberg, 1998, for a review of non-linguistic deficits that can accompany the linguistic problems in SLI.)

What to make of these more general symptoms? Several different explanations are possible. Some researchers have argued that the non-linguistic impairments are a clue that the underlying problem isn't specifically linguistic after all. Instead, they argue for a **domain-general perspective** that views SLI as a cognitive problem that's not particular to language in and of itself but that ends up having especially weighty consequences for language. Marc Joannise and Mark Seidenberg (1998) have argued that what starts as a general problem in processing the details of sounds, or in holding material in working memory, could have profound effects on the learning of language structure. Here's an example of how this could play itself out.

Many people with SLI have trouble with the small grammatical tags on words that mark that a verb is in the past tense or that a noun is plural (for example, *walked, bragged; dogs, minions, cakes*). What could be simpler? These verbs and nouns merely involve the addition of one extra sound. But, as pointed out in Section 2.3, the plural form of English actually involves a choice between two *different* sounds, the "s" sound and the "z" sound. Which goes where depends on the subtle properties of the sound that comes just before it—so you get the "s" sound after *fat*, but the "z" sound after *fad*. (You'll read in much more detail about this kind of sound variation in Chapter 4.) So, in order to

**domain-specific perspective** In regard to SLI, the situation in which the linguistic deficit strikes at mechanisms that are particular to language, rather than ones that are shared with other cognitive abilities.

**domain-general perspective** In regard to SLI, the situation in which the linguistic deficit is only one effect of more general cognitive problems that also affect non-linguistic processes.

grasp how plural formation works in English, a child has to be able to clearl distinguish between the sounds "s" and "z" and line up this difference with th difference between the sounds "t" and "d." Without this ability, the process c making plurals in English looks much more mysterious, and the end result ma be that children with SLI produce more random-looking plural structures, o leave off the marker altogether.

At the level of sentence structure, many important differences in structure and meaning are signaled by very small, meek-sounding *function words* Consider:

> The horse chased the man.
>
> The horse was chased by the man.

These sentences are essentially mirror images of each other when it comes to their meaning, yet they are distinguished only by presence of the little words *was* and *by*, neither of them uttered with any acoustic prominence (we don't normally say "The horse WAS chased BY the man," with stress on the small function words). If important grammatical markers like these are missed by children with an underlying sound-processing deficit, then learning to extract general rules about how sentences are put together, and about how structure relates to the meaning of a sentence, is certainly bound to be an uphill battle.

These examples give an idea of how struggling with the details of sounds might snowball into far-reaching problems with language structure. Under this processing-based explanation of SLI, what looks like "broken grammar" could be the end result of trying to learn structure on the basis of lousy input—maybe a bit like trying to learn a foreign language through the constant hiss of white noise. Similar stories could be told about other non-linguistic deficits commonly found among SLI populations, such as problems with working memory. The problem may *look* specifically linguistic simply because language makes especially heavy use of subtle distinctions among sounds, or often requires that long strings of words be held in working memory. Other functions might appear to be "spared" simply because they don't draw as heavily on these particular skills as language does—but it's the underlying *non*-linguistic skills that are damaged, and not the language-learning mechanism itself.

In response to such arguments, defenders of the "broken grammar" view have countered that the mere presence of non-linguistic deficits can't be construed as evidence that they *cause* the apparent problems with language. For instance, Heather van der Lely and Chloe Marshall (2011) take the position that these other cognitive deficits may coexist with the linguistic impairments, but that they don't really have anything to do with the language deficit itself. After all, even in a genetic disorder like Williams or Down syndrome, which can be traced back to a single chromosome, the cognitive impairments are also accompanied by other symptoms or features—for instance, certain typical facial characteristics, or congenital heart problems. Does this mean that the heart is part of the same "system" as the impaired cognitive functions? Hardly. Rather, the co-occurrence reveals that genes can sometimes have very diffuse effects, with ramifications for multiple systems at the same time. In order to show that the linguistic problems *stem* from the more general processing deficit, it's important to show that the severity of the linguistic impairment is clearly related to the severity of the more general processing deficit.

There's still a lot we don't know about the link between the language problems and more general cognitive anomalies of people with SLI (or other genetically linked language deficits such as dyslexia; see **Box 3.2**). A number of issues complicate the picture and will need to be carefully sorted out. For example,

## BOX 3.2
## Dyslexia: Is there a gene for reading?

Researchers know two salient things about specific language impairment (SLI): First, people who have it struggle with producing the right grammatical patterns and structures. Second, SLI has a strong hereditary basis. Thus, it's tempting to conclude that there are specific genes *for* grammar, and that SLI reflects the disruption of these genes. But to see the problem with this logic, it makes sense to look at disorders of reading.

**Developmental dyslexia** is a common learning disability that leads to difficulties in learning to read, but no apparent problems with spoken language or other learning problems. Dyslexia is also known to have a strong hereditary basis. So, should we conclude that dyslexia is basically a selective impairment of genes that are responsible for reading? Here's where that idea has trouble getting off the ground: Writing is a fairly recent invention—as a species, we've only been reading and writing for several thousand years, likely a much shorter time than we've been speaking. And while speaking (or signing) is universal among humans, many societies still exist without feeling the need to put things in writing. Moreover, even within societies that have had writing systems for a long time, it's only very recently that literacy has become common in the general population. This makes it highly implausible that, in such a short time, we could have evolved genes dedicated to the mastery of this recent, non-universal, elite cultural tool. What's more, there's no evidence that people who come from societies (and therefore gene pools) with very low literacy rates have any greater difficulty in learning to read than those who come from countries where a larger segment of the population has been reading for centuries. So, what to make of the connection between genes and reading?

A plausible explanation is that reading relies on genes that didn't develop *specifically* for reading, but that the affected genes contribute to a skill that turns out to be highly *relevant* for reading. A closer look at the abilities of people with dyslexia has turned up one consistent sticking point: difficulty with **phonological awareness**, or consciously analyzing strings of sounds into their subparts. For instance, many dyslexics have trouble with requests and questions like these:

> Which word has a different first sound: *beetle, bat, chair,* or *bust*?
>
> Say *catch*. Now say it again, but don't say the "k" sound.
>
> Here is a picture of a desk. Now finish the word for me: *des*__.

Some researchers have argued that this difficulty springs from a more general underlying problem in processing sequences of sounds. Whether or not this is true, it's easy to see how trouble in consciously isolating individual sounds from longer strings would be a problem for learning to read (at least in a writing system like ours): The whole enterprise hinges on matching up individual sounds with visual symbols. It's also easy to see why a subtle sound problem might turn up most glaringly as a reading problem: in understanding spoken language, one can get by without decomposing strings of sounds, but an inability to do so in the context of reading has more catastrophic consequences.

Dyslexia is an important example to keep in mind whenever you come across a connection between a genetic anomaly and a highly visible outcome—the causal chain between the genes and that outcome could be either very direct, or very indirect. The notion that genes have evolved specifically *for* that outcome is always, at best, a starting hypothesis that should provoke additional exploration.

---

**developmental dyslexia** A common learning disability with a strong hereditary basis that leads to difficulties in learning to read, without any apparent spoken language or other learning problems.

**phonological awareness** The ability to consciously analyze and separate strings of sounds into their subparts.

it's unlikely that SLI makes up a single disorder with a single underlying cause. There's quite a bit of variability in the linguistic and non-linguistic profiles of people who have been diagnosed as having SLI. This has led researchers to suggest that SLI is a catchphrase for a cluster of different disorders, all of which end up disproportionately affecting language function. If that's the case, then sorting out cause-and-effect explanations is going to require making the right distinctions among different subtypes of SLI.

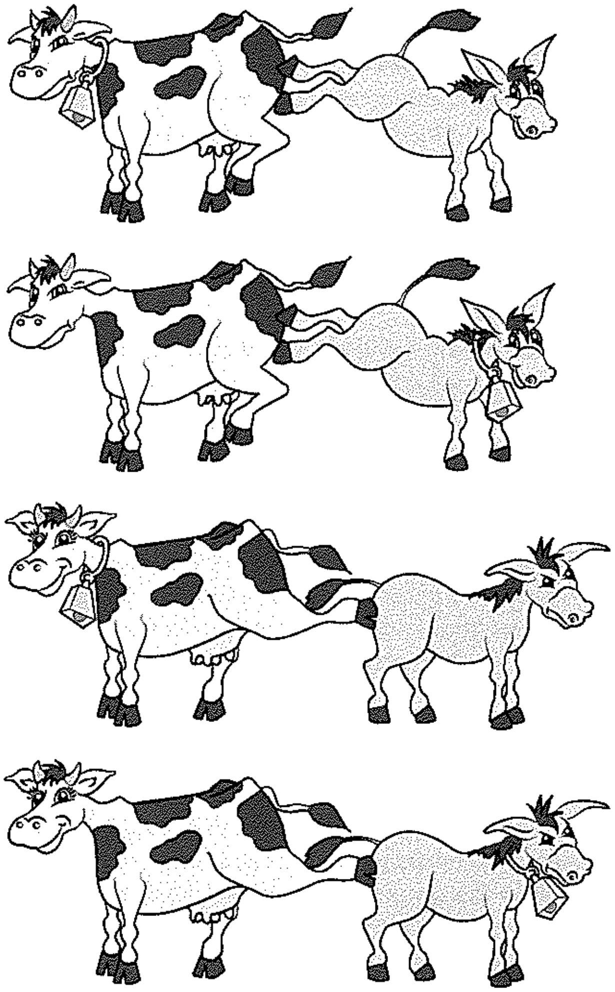


**Figure 3.2** Sample stimuli from a sentence picture verification task. Children are asked to point to the picture that matches the sentence "The donkey that kicked the cow has a bell."

WEB ACTIVITY 3.1

**Cognitive demands in language tests** In this activity, you'll explore several tests that have been used to test language functioning in SLI. You'll consider what other cognitive skills might be necessary to succeed at the task, in addition to the targeted linguistic skill.

### *Testing the right thing: Method is important*

There's an important methodological issue to take into consideration when trying to figure out how linguistic skills relate to non-linguistic ones: in order to measure language function, we have to rely on some appropriate test. But the test itself may depend on cognitive skills over and above the specific linguistic skills that are being targeted. For example, a common way to test how well children understand syntactic structure is to present them with a series of test trials involving complex sentences that differ in subtle ways, such as "The donkey that kicked the cow has a bell" versus "The donkey kicked the cow that has a bell." Children are shown several pictures and are asked to choose which picture best goes with the sentence they just heard (see **Figure 3.2**). In order to perform reliably on this test, children need to have intact syntactic skills. But they also need to have several other things: the perceptual skills to make fine distinctions among similar images; the ability to relate visual images to representations of similar events; the memory capacity to keep track of which pictures differ how; the memory capacity to remember exactly what sentence the experimenter uttered; the motivation to repeatedly pay attention to a series of test trials; and so on. This test—intended to probe for syntactic understanding—is hardly purely linguistic. So, let's suppose we find that children who have especially short memory spans do worse on this test than those with roomier memory spans. Does this mean that the children's difficulty with syntax can be explained as originating in problems with working memory? Not necessarily—it may just be that *this particular test* relies heavily on working memory, creating a false connection between memory and syntactic performance. Ideally, we'd want to check to see if the relationship holds across a number of different tests probing for syntactic understanding and memory, using tests that vary in the ways in which they tax non-linguistic cognitive functions.

### *We need more knowledge about how language works*

The title of this section is "What can genetic disorders tell us about brain systems?" Perhaps it's time to take a stab at an answer, based on the research survey so far. The fact that there's a variety of different genetic disorders, with strikingly different effects on both language and general cognition, shows that there is some degree of specialization in the brain, and that genes can affect how these specialized skills develop. At the same time, evidence from language disorders doesn't offer us an easy picture, with a clear division between language and the rest of the brain. Instead, it looks as if we'll need to look deeper, to study the various skills that make up the collection of behaviors we call "linguistic."

In a way, none of this should come as a surprise; it roughly parallels the conclusion we drew at the end of the last chapter about the evolution of language. Language doesn't appear to be a self-contained, all-or-nothing bundle of abilities. We saw that different non-human species show different patterns of strengths and weaknesses in their aptitudes for the various skills that go into learning and using language. For example, chimps show some ability to master the use of symbols, but they have virtually non-existent vocal imitation skills; songbirds show vocal virtuosity in the wild, but there is no evidence that they use their abilities to convey meaning. Language, it seems, is a fortuitous coming together of all the pieces required to make it work—whether these pieces are specifically linguistic skills or more general ones that support it—and this appears to be reflected as well in those situations where something goes wrong in the human brain's ability to pull it all off.

But an important lesson from the study of genetic disorders is that in order to properly understand them, we're going to need a detailed body of knowledge that encompasses all the machinery that goes into learning, processing, and producing language. After working your way through this book, you should have a much better sense of just how intricate this machinery is. There's still much basic work to be done, but ultimately, a careful study of genetic language disorders is likely to provide some important insights about which component skills seem to cluster together, and which ones seem to be less closely related. Ultimately, this may give us a useful angle on thinking about how brain systems might be organized and genetically influenced.

## 3.2 Where in the Brain Is Language?

In the previous section, I suggested that genetic disorders that affect some skills while leaving others intact can provide clues about underlying neural structures. But language disorders can arise for reasons other than genetic anomalies that are present from birth. They can also happen at any point in life as a result of damage to the brain through stroke, seizures, or simply a very unlucky accident. In theory, disorders from brain damage can provide even more direct information about the relationship between the brain's anatomy and its functions, since in many cases, it's possible to see *where* the brain has been damaged.

### *Early ideas and discoveries: The case of Phineas Gage*

Physicians' records from as far back as the seventeenth and eighteenth centuries document several types of lost language function and try to explain the cognitive nature of these losses. But it wasn't until the nineteenth century that scientists began to develop serious theories about how linguistic functions might actually be implemented in brain matter. This reflects how deeply mysterious the brain was until fairly recently. Nowadays, we take it for granted that we can record detailed images of living brains, and it's common knowledge that different parts of the brain carry out different tasks. But the very notion that the brain is divided up into different regions that perform specific functions was not widely accepted by scientists until about 150 years ago.

Early ideas about the localization of brain function began to gain steam in the 1800s and came largely from observing the effects of brain damage—the kind of devastating damage that obliterates brain tissue in ways that can easily be seen. One of the most famous case studies is that of Phineas Gage, a

25-year-old railroad worker. In 1848 Gage was the unfortunate victim of an accidental explosion that drove an iron rod into his left cheek and out the top of his head, landing about 25 meters away. Incredibly, Gage not only survived, but moments after the accident, sat up and chatted, and a short while later was able to relate the details of the accident to a doctor. He survived for more than 12 years with most of his capacities seemingly intact—his language and motor function, for example, appeared to be fine. The doctor who cared for him noted that Gage's survival was surely due in part to the fact that "the portion of the brain traversed, was, for several reasons, the best fitted of any to sustain the injury." But he also noted that the accident had caused some deep changes; evidently Gage's personality took a turn for the worse, and he was never able to function as well as he had before the accident (see **Box 3.3**).

## BOX 3.3

## Phineas Gage and his brain

Dr. John Martyn Harlow was practicing in Cavendish, Vermont, near where Gage's accident occurred in 1848. He treated Gage at the time and followed his patient's progress until Gage's death in 1860. Harlow then prepared a detailed summary of the case (he even obtained and studied Gage's skull), which was published in 1868 and describes Gage's altered personality:

> *The equilibrium or balance, so to speak, between his intellectual faculties and animal propensities, seems to have been destroyed. He is fitful, irreverent, indulging at times in the grossest profanity (which was not previously his custom), manifesting but little deference for his fellows, impatient of restraint or advice when it conflicts with his desires, at times pertinaciously obstinate, yet capricious and vacillating, devising many plans of future operations, which are no sooner arranged than they are abandoned in turn for others appearing more feasible. A child in his intellectual capacity and manifestations, he has the animal passions of a strong man. Previous to his injury, although untrained in the schools, he possessed a well-balanced mind, and was looked upon by those who knew him as a shrewd, smart businessman, very energetic and persistent in executing all his plans of operation. In this regard his mind was radically changed, so decidedly that his friends and acquaintances said he was "no longer Gage."*

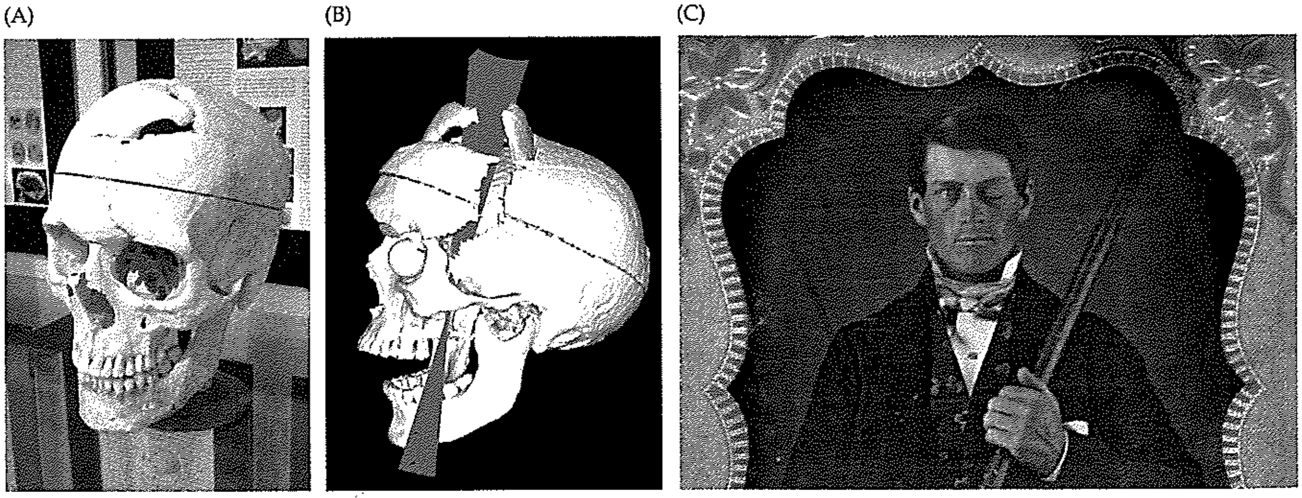


**Figure 3.3** (A) Phineas Gage's skull is on display at the Warren Anatomical Museum at Harvard Medical School. (B) Reconstruction of the pathway of the iron rod through Gage's skull. (C) A recently discovered photograph of Gage (holding the iron rod), taken some time after his accident. (A,B from Van Horn et al., 2012; C from The Jack and Beverly Wilgus Collection.)

The case of Phineas Gage was widely publicized. He became an attraction at Barnum's American Museum in New York and toured New England as a traveling exhibit. The details of his accident and recovery aroused the morbid curiosity of the general public, but also the interest of scientists. At the time, the idea that the brain was made up of a number of independent regions, each responsible for different functions, was a new and controversial one. The more traditional view was that the brain functioned as an undifferentiated mass of neurons. But Gage's accident lined up with a number of observations that had been made earlier, in which doctors had pointed out that damage to the brain could have very uneven effects: sometimes a very slight injury to the brain could be fatal, while at other times large swaths of the brain could be damaged with surprisingly little effect. The only possible explanation for this was that different parts of the brain play different roles. David Ferrier, one of the earliest champions of the idea of brain localization, used the Gage case as a centerpiece in his well-known lectures, and as the basis for experiments with monkeys.

And yet, as a scientific case study, the Gage incident falls short on evidence. Other than stimulating interest in a budding idea, its scientific contribution is slender, verging on downright skeletal. There aren't enough facts to be able to draw any clear conclusions about the connection between the damaged parts of Gage's brain and the effects of the trauma on his brain function. Since no autopsy was done, there isn't even a clear picture of exactly what tissue was affected. Moreover, the observations of his behaviors after the accident are unsystematic, and no detailed testing was ever undertaken (Macmillan, 2008). All that we have are the very impressionistic remarks of his physician. From a modern perspective, it's astonishing how little in the way of useful scientific evidence was salvaged from the tragic event. In the hands of a neuropsychologist today, Gage would likely have been put through many batteries of tests to reveal detailed profiles of his cognitive functioning. How could so little scientific value have been pulled out of such a potentially important case?

In the historical context, though, we shouldn't be surprised by the lack of rigorous study applied to the case. Scientists at the time quite literally didn't know what to look for. There was very little understanding of what the brain was *for*, even in a very general sense. It was widely accepted that the brain regulated movement and the senses—this was known from the physical evidence of how the nervous system extends from the brain into the body's muscles and sensory organs. But it wasn't even taken for granted that more abstract aspects of the mind like language or higher intellectual functions—let alone things such as *character* or *temperament*—were under the brain's command. There was simply no framework within which to start testing the various functions that might have been disrupted by Gage's accident.

So perhaps one of the greatest scientific lessons to take from the famous case of Phineas Gage is that in order to make real progress in understanding the brain, an examination of the physical object of the brain has to proceed in lockstep with some sound thinking about the brain's job description. As we'll see in the next section, this applies as much in these days of high-tech brain scans as it did in 1848.

### Evidence for language localization: Broca and Wernicke

If there was any doubt in Gage's time that language "lives" in the brain, this was quickly dispelled, largely through the influential work of Paul Broca. In 1861, Broca examined a patient by the name of Leborgne who suffered from a brain condition that had caused him to have seizures from a young age and had left him unable to move one side of his body and unable to speak—aside from

**cerebral cortex** The outer covering of the brain's cerebral hemispheres.

**aphasia** Any language disruption caused by brain damage.

**Broca's aphasia** Aphasia characterized by halting speech and tremendous difficulty in choosing words, but fairly good speech comprehension. Also called motor aphasia or expressive aphasia.

**Wernicke's aphasia** Aphasia associated with fluent speech that is well articulated but often nonsensical, and enormous difficulty in understanding language. Also called sensory or receptive aphasia.

a particular swear word, the syllable *tan* was the only set of speech sounds he'd managed to eke out for 21 years. The patient died a few days after their meeting, and as Broca was aware that scientists were beginning to explore claims about the localization of language, he decided to autopsy Leborgne's brain. He considered language to be a good test case for the more general hypothesis that the various functions of the brain were compartmentalized into different physical regions. He discovered extensive damage to the frontal lobe on the left side of Leborgne's brain, providing some of the earliest hard evidence of localization in the brain (Broca, 1861).

Based on his observations, Broca argued that the faculty of language was further split apart into subfunctions, an idea that was consistent with many earlier reports of language loss due to brain damage. He noticed that Leborgne seemed to understand language much better than you'd expect from his utter lack of ability to speak—for example, when asked how long he'd been hospitalized, he flashed four sets of five fingers and then a single finger, to indicate 21. To Broca, this suggested that he'd lost the ability to produce spoken language (despite maintaining reasonable dexterity of his tongue and mouth) but that other aspects of language functioning were better preserved. Following this famous case, Broca autopsied the brains of a number of patients whose language was impaired after stroke or other brain damage, and he found that a significant portion of them had damage to the same part of the **cerebral cortex** (the brain's outer layer of neurons), specifically on the left side of the frontal lobe.

Shortly after Broca's discovery, neurologist Carl Wernicke studied a patient who had suffered a stroke and, though able to speak fluently, didn't seem to understand anything that was said to him. A later autopsy revealed a lesion, or evidence of brain damage, on the left side of the cerebral cortex—but the lesion was farther back than the region Broca had described, in the temporal lobe rather than the frontal lobe (see **Figure 3.4**).

In 1874, Wernicke published an influential text in which he explored his ideas about **aphasia**, the clinical term for language disruption caused by brain damage. Even though scientists and clinicians had long suspected that language loss came in at least two distinct varieties, the pioneering work of Broca and Wernicke established that the distinct forms of aphasia were related to different areas of the brain. **Broca's aphasia** (also called motor or expressive aphasia) is characterized by halting speech, if any at all, and tremendous difficulty in choosing words, but fairly good comprehension. **Wernicke's aphasia** (also called sensory or receptive aphasia) is associated with fluent speech that is well articulated but often nonsensical, and enormous difficulty in understanding language. (See **Table 3.2** for examples of speech by patients with Broca's and Wernicke's aphasias.)

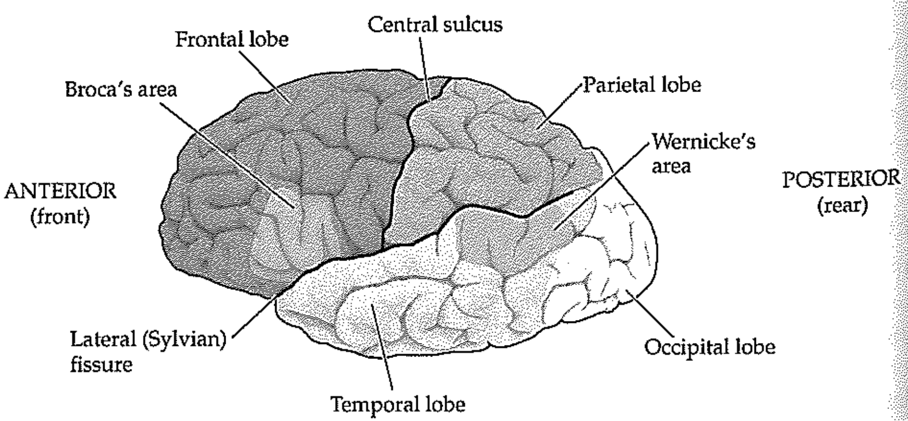


**Figure 3.4** A side view of the surface of the brain's left hemisphere. The four lobes of the cerebral cortex are indicated in shades of gray, with Broca's area and Wernicke's area shown in color.

**TABLE 3.2 Examples of speech from patients with Broca's and Wernicke's aphasias**

**Patient with Broca's aphasia, re-telling the Cinderella story:**[a]

Cinderella uh... scrubbing and uh... hard worker. Step fa... mother uh go... but no. Scrubbing uh uh wathacallit uh uh working. Stepmother really ugly. Dress break... stepmother and now what dress? Mother Teresa... not exactly... uh uh magic godmother! Dress... beautiful and carriage where? I can uh... pumpkin and uh... servants and horse and beautiful carriage and so magic. But, better midnight... pumpkin carriage gone. Cinderella dance. Midnight uh clock uh Cinderella clock! Slipper fall. Prince can't uh stepmother fitting slipper? Cinderella where? Well locked. Sure enough fits because Cinderella uh... magic uh... girl. And probably uh prince and Cinderella marrying and happy. That's it.

**Patient with Wernicke's aphasia, reporting on suffering a stroke:**[b]

It just suddenly had a feffort and all the feffort had gone with it. It even stepped my horn. They took them from earth you know. They make my favorite nine to severed and now I'm a been habed by the uh starn of fortment of my annulment which is now forever.

[a] From Thompson, 2008.
[b] From Dick et al., 2001.

## *Creating brain maps for language*

As you've seen, we owe much of our foundational understanding of brain localization to accidents of nature, and to the clinicians who made intelligent observations about the behavior of the unfortunate victims. Further progress came from the pioneering work of neurosurgeon Wilder Penfield, who produced detailed maps of human brain function as part of his surgical treatment of patients with brain tumors or epilepsy (Penfield & Jasper, 1954). To identify indispensable parts of the brain in order to avoid removing them during surgery, Penfield and his colleagues used a procedure for electrically stimulating the brain while the patient was conscious. This stimulation would temporarily disrupt brain function, and the patients' responses were used to pinpoint the sites of specific brain functions in individual patients. By carefully recording the results from many patients, Penfield confirmed that stimulating Broca's and Wernicke's areas often caused problems for language production and comprehension.

But Penfield's studies also showed a surprising amount of variation among individuals. Some patients seemed to have no impairments even when Broca's area was stimulated, while others were rendered mute or incapable of comprehension when regions far outside the expected language areas were targeted. More recent work has confirmed that individuals can vary a great deal when it comes to where in the brain they carry out the same language tasks. This is especially likely to be true of people with damaged brains; unlike the body's physical organs, where lungs can't take over the functions of damaged kidneys, for example, the brain does have a sometimes startling ability to reorganize itself to compensate for damage, especially if the brain damage occurs in a young person. For instance, there have been cases where children have had their entire left hemispheres removed because of enormous amounts of epileptic activity; in some of these, the kids have grown up to have near-normal use of language (de Bode & Curtiss, 2000).

Aside from individual variation, there are other reasons to believe that most people carry out important language-related tasks not just in Broca's and Wernicke's areas, but also in regions far outside of these areas, including in the right hemisphere, and in areas beneath the cerebral cortex (the **subcortical** areas of

**subcortical** Refers to the internal regions of the cerebral hemispheres, lying beneath the cerebral cortex.

the brain). In fact, even the dramatic language impairment of Broca's famous patient named Leborgne may have resulted from more extensive damage than Broca originally thought: since the good doctor had the incredible foresight to preserve Leborgne's brain for future scientists, researchers were recently able to image the brain using modern magnetic resonance imaging (MRI) techniques. They found evidence of deep damage to the brain not just in the frontal lobe on the left side, but also in subcortical areas and throughout the superior longitudinal fasciculus, a bundle of neurons that connects the front and back areas of the cerebral cortex (see **Figure 3.5**).

It's apparent that the divide between comprehension and production is not a tidy one. On closer inspection, most patients with Broca's aphasia have trouble with some aspects of comprehension as well as devastating difficulties with language production. Especially irksome for these patients are sentences that rely on subtle or complex syntactic structure without any helpful clues about meaning. (For example, a Broca's patient might readily figure out the meaning of *The mouse was chased by the cat* but not *The boy was chased by the girl*. For the first example, but not the second, the meaning of the sentence can be plausibly assembled if all you can figure out are the word meanings.) Symptoms like these have prompted researchers to offer various proposals about additional duties of Broca's area. Some have argued that certain kinds of syntactic structures are computed in this region; others have suggested that it's an important site for working memory processes, or for mechanisms that resolve the tension between conflicting linguistic cues. This rethinking of the nature of aphasia is driven in part by more detailed techniques for studying the brain. But it also comes from much more detailed theories about all of the mental operations that are involved in producing and understanding language. And as these theories become richer and more complex, so do ideas about how language function maps onto areas of the brain.

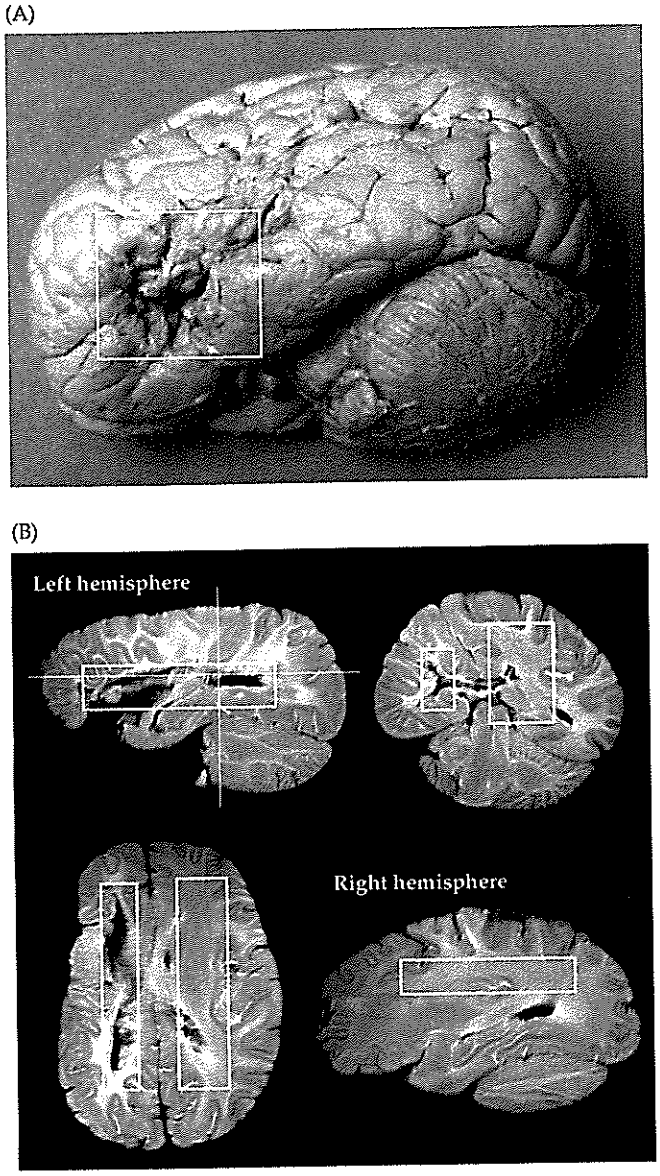


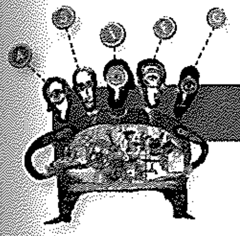
**Figure 3.5** (A) Photograph of Leborgne's brain, with damage clearly visible in the inferior frontal lobe of the left hemisphere. (B) MRI images showing extensive damage throughout the left hemisphere. Boxes are drawn around comparable areas in the left and right hemispheres. (From Dronkers et al., 2007.)

## Brain lateralization

The fact that Broca's and Wernicke's areas were both traced to the left side of the brain led to the first inkling that the brain might be organized differently in its two hemispheres—a possibility that initially came as a great surprise to Paul Broca. But since Broca's time, additional evidence of **brain lateralization** (that is, evidence that the right and left cerebral hemispheres are specialized for different functions) has come from many corners, and has involved somewhat exotic brain conditions as well as clever studies of people with uninjured brains.

**brain lateralization** The specialization of the brain's right and left cerebral hemispheres for different functions.

The best-known studies of brain lateralization were done by Roger Sperry and Michael Gazzaniga in the 1960s, about a hundred years after the pioneering work of Broca and Wernicke. The studies involved a number of "split-brain" patients who had undergone a radical, last-resort treatment to prevent the spread of epileptic seizures from one side of the brain to the oth-



## LANGUAGE AT LARGE 3.1

### One hundred names for love: Aphasia strikes a literary couple

Aphasia opens a fascinating scientific window into the brain, but in the lives of those who experience it, it mostly feels like a closing down of connections to others. One of the most moving and complex personal accounts of aphasia comes from American author Diane Ackerman. In her book *One Hundred Names for Love* (2012), she chronicles the stroke and subsequent aphasia suffered by her husband Paul West, a novelist himself.

West came out of his stroke able to utter only a single syllable (*mem*), apparently baffled that others couldn't understand him. It's hard to imagine a couple for whom the loss of language would be more devastating. Ackerman relates how, before her husband's stroke, many of their intimate moments centered on impromptu language games. And she described her husband Paul as a man who "had a draper's touch for the unfolding fabric of a sentence, and collected words like rare buttons."

Through intense effort, Paul was able to recover a good amount of language function, possibly with the help of his dazzling collection of words. When the route to a familiar word was blocked, he was sometimes able to take a neural detour to unearth another one that would serve his purpose. He struggled with words like *blanket* or *bed*, or his wife's name, *Diane*. Nonetheless, he could recruit words like *postilion* or *tardigrades* to get an idea across. Occasionally, he even sent his verbally endowed wife scrambling for a dictionary. In trying to ask her whether she'd received a check she'd been waiting for, he resorted to the word *spondulicks*, which prompted the following exchange:

> *'What's a spondulick?'*
>
> *'Money.'*
>
> *'Really? Truly? Spondulick?' In my mind's eye I picture a spastic duck.*
>
> *'Yes,' he said emphatically.*
>
> *'Spondulicks?'*
>
> *'Spondulicks. It's British.'*
>
> *Surely he was pulling my leg. I breezed into the library to look it up in an etymological dictionary, where I found this entry:*
>
> *1856, Amer. Eng. slang, 'money, cash,' of unknown origin, said to be from Gk. spondylikos, from spondylos, a seashell used as currency (the Gk. word means lit. 'vertebra'). Used by Mark Twain and O. Henry and adopted into British English, where it survives despite having died in Amer. Eng.*

Paul West even recovered sufficiently to write an account of his stroke, *The Shadow Factory* (2008). In it, his off-kilter language and sense of humor combine to give the text a vivid and disorienting effect appropriate to the topic. In the following passage, West describes how the stroke left him with trouble swallowing liquids; in order to prevent him from choking on them, they had to be thickened into semiliquid form:

> *If I were to take a drink from the wrong kind of liquid, I would in all probability aspirate and, having filled my lungs with fluid, choke and die. This unseemly possibility has three stages. The first is pudding, which in no sense imperils you; the next is honey, which puts you in less jeopardy; third is nectar, and finally water, when you are dicing with life and death. If all this sounds mumbo jumbo to an educated audience, it should not. For anyone intending to drink beyond his means, the risk of suffocation is high. For my own part, being on pudding as I was, I was consigned to eat chocolate pudding but shrank from eating the obscene mixture called pudding water, by which a mixture was made of water and thickener until the spoon was standing straight up. Such licentious behavior on the part of English pudding makers may surprise no one, but it may reveal to countless consumers of coffee, tea, and other drinks the perilous condition that they are subjecting themselves to if they drink water that goes down the wrong pipe.*

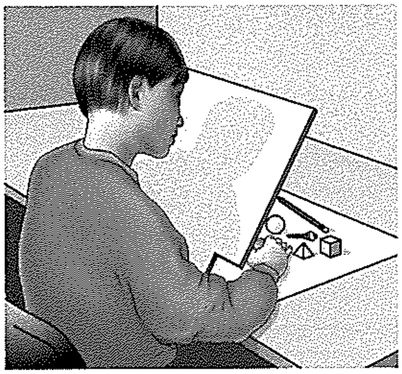
Paul and Diane were even able to resume their intimate wordplay, with adjustments for Paul's various linguistic detours. Sometimes this led to delightful results, when Paul bestowed new terms of endearment upon his wife, whose actual name he was often unable to produce. Among his various offerings were the following exquisite pet names: *My Little Bucket of Hair; Commendatore de le Pavane Mistletoe; Dark-Eyed Junco, My Little Bunko;* and *Diligent Apostle of Classic Stanzas.*

**corpus callosum** A bundle of neural fibers that connects and transfers information between the two hemispheres of the brain.

er. These patients submitted to a surgery that severed the **corpus callosum**, the bundle of neural fibers that connects the two hemispheres of the cerebral cortex in a high-speed "superhighway." The surgery was approved as a treatment after studies by Roger Sperry showed that the procedure in monkeys resulted in very little change in the monkeys' behavior—and indeed, human split-brain patients were able to function surprisingly well even though their two hemispheres had lost the ability to share information with each other.

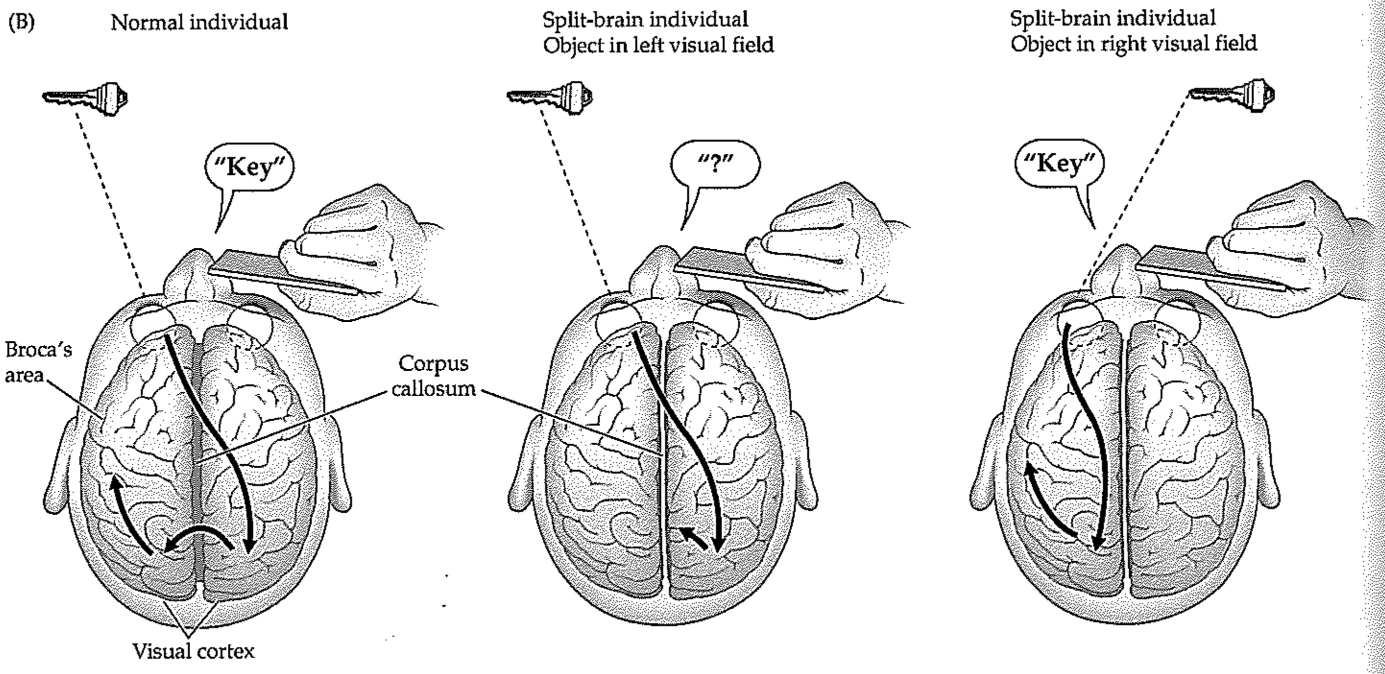
But using clever experimental tests, the researchers were able to demonstrate some bizarre consequences of the disconnection. The experiments required finding some way to present information to only one side of the brain. For example, to present information to the left hemisphere, sensory input needs to come from the right side of the body because the brain is wired in such a way that it receives input from, and sends motor commands to, the opposite side of the body. "Split-brain" patients used their right hands to handle objects that were hidden behind a barrier, so that only the left hemisphere had access to information gleaned from touching the objects (see **Figure 3.6**). In other versions of the experiments, patients sat in front of a screen and were told to look

(A)



| Left hemisphere functions | Right hemisphere functions |
|---|---|
| Analysis of right visual field | Analysis of left visual field |
| Stereognosis (right hand) | Stereognosis (left hand) |
| Lexical and syntactic language | Emotional coloring of language |
| Writing | Spatial abilities |
| Speech | Rudimentary speech |

**Figure 3.6** (A) A split-brain patient handles an object behind the screen with his right hand. (B) Presenting visual information in just the left or right visual field has different effects on individuals with normal versus split brains. When the corpus callosum is intact, information presented in the left visual field is processed in the right hemisphere but can be relayed to crucial language areas in the left hemisphere. In a split-brain individual, only information presented in the right visual field is able to reach the language areas in the left hemisphere.



at a dot in the middle of the screen. Just to the right of the dot, a written word or picture of an object would flash—too quickly for them to move their eyes, but long enough for them to read it or recognize it. This allowed the researchers to make sure that the visual information was available only in the right visual field (that is, the right side of what both eyes take in).

In situations like these, in which the stimulus was presented to the right hand or right visual field—and therefore processed by the *left* hemisphere—the patients had no trouble naming the object or word. However, when the information was presented to the left hand or left visual field, and hence processed by the *right* hemisphere, the patients drew a verbal blank. For a visually presented stimulus, they often reported just seeing a flicker, or nothing at all. At the same time, if asked to identify the object from among a set of picture cards, or even to draw the object with their left hand, they could do it, showing that they had recognized the object. But the part of their brain in the right hemisphere that had recognized the object was unable to communicate with the language areas in the left, leaving them incapable of *reporting* that they had seen it, much less naming it (Gazzaniga & Sperry, 1967).

WEB ACTIVITY 3.2

**Split-brain studies** In this activity, you'll view video footage of a split-brain patient performing the classic Sperry-Gazzaniga tests.

The fascinating results from the split-brain studies reveal two "half-minds" at odds with each other, with one hemisphere clearly more devoted to language than the other. But even if you have an intact corpus callosum, you too can contribute to brain lateralization science. Experiments with people whose cerebral hemispheres are properly connected have also yielded evidence of language specialization in the left hemisphere, through a task known as **dichotic listening**. In this test, subjects listen to spoken words over headphones. The twist is that a *different* word is spoken into each side, so the left ear, for example, might hear *dog* while the right ear hears *cat*. Most people can tell that each side hears a different word, but usually one of the words seems more distinct than the other. When asked to report what they heard, most people show an advantage for words piped into the right ear—that is, into the left hemisphere, the presumed seat of language. Why would this be, since the right hemisphere is connected to the left in these subjects, with unimpeded communication between the two sides? Regardless of which ear the sounds are coming into, they need to travel to the language areas in the left hemisphere, where their linguistic content can be identified. When the sounds are coming through the right ear into the auditory center in the left hemisphere, the distance to the language areas is shorter, giving these words a jump start. Sounds coming through the left ear into the auditory center in the right hemisphere have to travel a slightly longer distance, so by the time they're processed in the language center, the representations of the words that were delivered to the left hemisphere already have a competitive advantage.

WEB ACTIVITY 3.3

**Dichotic listening task** In this activity, you'll have the opportunity to test whether you show a right-ear (left-hemisphere) advantage for processing words.

## 3.3 Mapping the Healthy Human Brain

The earliest insights about the localization of language in the brain came from damaged or anomalous brains. But ultimately, the field of neurolinguistics needed to be able to study healthy human brains in order to confirm and extend the findings of early researchers like Paul Broca and Carl Wernicke. One reason for this is that there's no guarantee that the areas that perform certain functions in a damaged brain line up with the areas for the same functions in a normal brain. We now know that the brain has a truly impressive capacity to

**dichotic listening** Experimental task in which subjects listen to spoken words over headphones, with a different word spoken into each ear.

reorganize itself, and that even within a few weeks of a stroke, there's evidence that brain function has been rerouted in significant ways. If a function that was previously accomplished by a now-damaged area becomes taken over by a healthy part of the brain, it makes it hard to know what the original organization of brain function was like. There are other more practical challenges that come with relying on individuals with brain damage as the primary research participants. There's a relatively small number of them, which limits how much researchers can generalize to the broader population. It also constrains the amount of research that can be carried out; many individuals with brain damage are extraordinarily generous with their time in helping researchers make progress in the field, but there's a limit to how many hours any one person can spend in a lab performing tests—those who are recovering from a stroke, in particular, may tire easily, or they may show inconsistent performance partly because of their brain injury. Being able to test hypotheses within the general population was necessary in order for the field to make rapid progress and gain greater confidence in its findings.

### *Localizing language: Brain mapping techniques*

Although the possibility of large-scale testing of brain function in healthy humans had to wait until the advent of modern imaging techniques, some groundbreaking contributions to the science of brain localization were made more than a century ago. Among the most influential was the brain-mapping work of German neurologist Korbinian Brodmann, published in 1909. Brodmann believed that the study of brain function had to be grounded in a solid understanding of how the brain was built, so he set about meticulously analyzing the cellular composition of countless slices of brain tissue from animals and human cadavers. Based on his work, he created a "map" of areas in the human cerebral cortex that were anatomically distinct from each other (see **Figure 3.7**). His reasoning was that areas that differed in their physical structure were likely to be responsible for different functions. These **Brodmann areas** have guided much of the exploration of brain function, and are still commonly referred to in current cognitive neuroscience.

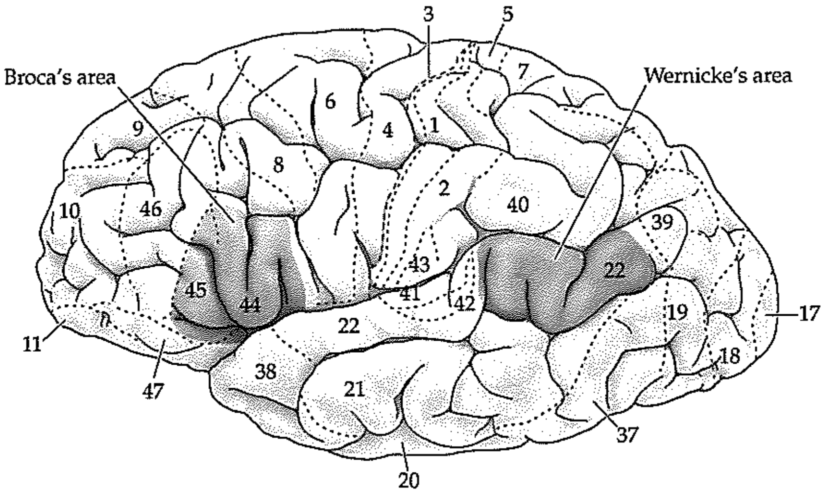


**Figure 3.7** The Brodmann areas of the brain mark distinctions in cell composition in the various layers of tissue in these regions. Broca's area corresponds approximately to Brodmann areas (BA) 44 and 45, while Wernicke's area corresponds to BA 22.

**Brodmann areas** Areas of the human cerebral cortex that are distinct from each other anatomically and in cellular composition, as determined by Korbinian Brodmann.

But how to link up the Brodmann areas with the activities of a healthy brain? A number of these areas were quickly aligned with specific functions, based on experiments with animals in which parts of the brains were electrically stimulated, or in which probes could detect the firing of individual neurons in response to specific stimuli. But these techniques were too invasive to be used with humans, and since language is unique to humans, more detailed localization studies of language lagged behind the study of other basic functions, such as vision. A major technical breakthrough occurred in the early 1990s with the development of fMRI.

It would be a gargantuan understatement to say that the availability of **functional magnetic resonance imaging**, or **fMRI**, has stepped up research activity on brain localization. Over the last two decades, tens of thousands of studies have been published using this method, most of them imaging the uninjured brains of healthy subjects. In popular science writing, it's common to read about fMRI showing brain regions "lighting up" in response to certain stimuli—images of loved ones, or of Hillary Clinton, or an iPad, or whatever. But the fMRI isn't measuring brain activity *directly*. Instead, it's using magnetic field differences to detect and record normal physiological differences in oxygen-rich blood versus oxygen-poor blood. From these **hemodynamic changes**—changes in the blood oxygen levels and direction of blood flow in various areas of the brain—scientists *infer* that brain regions with higher levels of blood flow or blood oxygen are more active. The basic principles underlying fMRI are similar to those of an older technique, **positron emission tomography**, or **PET**. In PET, hemodynamic changes in the brain are made visible by means of a radioactive tracer in the subject's bloodstream. PET is a useful research tool, but it hasn't seen the same massive research application with healthy human subjects that fMRI has, in part because it's a riskier technique, requiring exposure to radiation.

One of the earliest scientists to make the connection between blood flow and brain activity level was Angelo Mosso in the 1870s and 1880s. This connection was based on his observations of a patient named Bertino, who had suffered a head injury that left him with part of his frontal lobes visibly exposed (Raichle, 2000). Mosso noticed that the exposed part of Bertino's brain would pulse more vigorously when the patient heard the chime of church bells, or a clock that signaled time for prayer. Suspecting that the pulsing had something to do with Bertino's thoughts about prayer, he put this question to the patient, and watched Bertino's brain pulse as he thought about it and answered yes.

Mosso, too, struggled with how observations based on injured patients could be extended to the non-invasive study of human subjects in the general population. He eventually conducted a series of experiments using a human balancing device (see **Box 3.4**); the subject lay on a horizontal platform with the head on one side of the pivot and feet on the other, with the two sides perfectly balanced. Mosso assigned the subject tasks that called for various degrees of mental effort, in order to see whether the increase in blood flow to the brain would cause the head to tip lower than the feet, presumably because of the increase in blood flow to the brain (Sandrone et al., 2013). The method was primitive, but it shares the same assumptions as current, highly sophisticated brain-imaging techniques. It's also important to remember that, while the connection between measures of blood flow and brain activity is on the right track, even modern techniques can miss details that occasionally turn out to be supremely relevant for interpreting imaging studies. Brain regions reflect massive populations of neurons, not all of which necessarily carry out the same function. Therefore, fMRI might show an area as basically unresponsive to a certain stimulus even though a minority of its neurons are eagerly firing away.

**functional magnetic resonance imaging (fMRI)** Neuroimaging technique that uses magnetic fields to measure hemodynamic changes in the brain while the brain is engaged in a task, on the assumption that such changes are a measure of brain activity.

**hemodynamic changes** Changes in blood oxygen levels and direction of blood flow.

**positron emission tomography (PET)** Neuroimaging technique that uses radioactivity to measure hemodynamic changes.

## BOX 3.4

### Then and now: Measuring brain activity through blood flow

In the late nineteenth century, the Italian physiologist Angelo Mosso observed a brain-injured patient and, based on his observations, made a connection between mental activity and blood flow in the brain. He later devised a "human balancing device" on which he tested his sense of this connection by conducting non-invasive studies of healthy individuals. The subject lay on a horizontal platform with the head on one side of a pivot and feet on the other, with the two sides perfectly balanced (see **Figure 3.8A**). Mosso assigned the subject tasks that called for various degrees of mental effort, in order to see whether this mental effort would cause the head to tip lower than the feet—a presumed consequence of increased blood flow to the brain. As Sandrone et al. (2013) describe:

> *Mosso nicknamed his device "the machine to weigh the soul." He reported that the balance tipped towards the head when subjects were given more complex tasks; for instance, more head-tipping occurred while reading a page from a mathematics or philosophy text than when reading a novel. He also claimed to see effects of emotionally charged stimuli. For instance, he reported that the balance tipped toward the head immediately when one of his subjects read a letter from his spouse, and another read a note from an upset creditor. Media hype was just as present in the day of Mosso's balance as with today's fMRI studies, with a French newspaper reporting in 1908 that the device would "soon fully explain the physiology of the human brain" and lead to new treatments for neurological and mental illnesses.*

Mosso's method was primitive, but it's worth remembering that it shares the same starting assumptions as our current, highly sophisticated brain-imaging techniques. Based on the assumption that active brain regions will display higher levels of blood flow and blood oxygen than inactive regions, modern fMRI machines use magnetic field differences to detect and record brain activity (see **Figure 3.8B**).

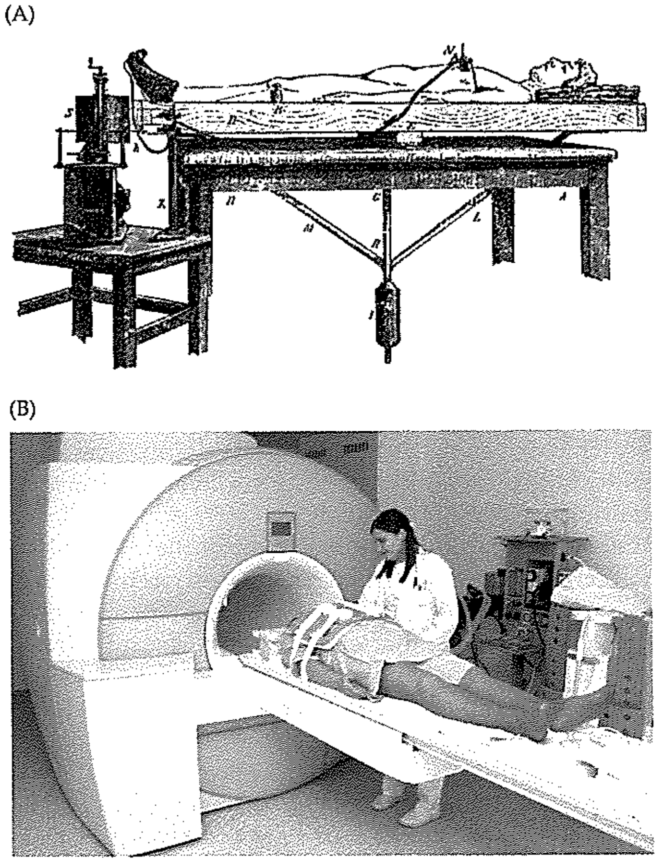


**Figure 3.8** (A) Mosso's balance for measuring blood flow. (B) A successor to Mosso's balance, a modern fMRI brain scanner. (A reprinted from Sandrone et al., 2013; B © Shutterstock.)

So, the first assumption that neuroscientists make is that there's a principled connection between hemodynamic measurements and brain activity. The second important assumption is that if changes in blood flow are consistently seen in certain areas of the brain shortly after the presentation of a certain stimulus, this is because the brain is recruiting those areas to process that type of stimulus. Relying on these two assumptions, how would we go about detecting the "language areas" of the brain in an fMRI experiment?

It's not quite enough just to show someone in a scanner an image of a word or sentence, or have her hear a snippet of speech, and then see which brain regions show a change in blood flow. First of all, hemodynamic changes happen even in a brain that's at rest (whatever *that* might mean), so these changes need to be factored out somehow (see **Method 3.2**). A more subtle and difficult point is this: How do we know that the active areas of the brain are engaged in processing the *linguistic* aspects of the stimulus? In reading a word, for example, there will be areas of the brain that are involved in very basic aspects of visual processing that have nothing to do with language—processes that would be just as active in, say, looking at an abstract painting, or recognizing a couch. Or, the word may trigger non-linguistic memories, associations, or thoughts,

## METHOD 3.2

### Comparing apples and oranges in fMRI

The pictures of activated brain regions that you see in published fMRI studies don't represent a snapshot of the activity of any one brain for the task in question. They're more sensibly read as graphs rather than photos, and they typically represent the *difference* between the experimental condition of interest and some chosen comparison condition, as averaged over many subjects. The dark areas in the picture don't mean that those areas of the brain weren't active while the task was being accomplished. They simply mean that those areas weren't *more* active—to a statistically meaningful degree—than they were during the comparison condition. This means that it's always worth thinking about what the comparison condition is, because the conclusions can only be stated in terms of this difference. A larger or smaller number of brain areas can show up as statistically different depending on the choice of the comparison condition. Let's consider some of the issues that might come up with a language task and various comparison conditions we might opt for.

A common comparison condition is to instruct subjects to close their eyes and think about nothing in particular. Suppose we wanted to use this condition as a baseline for a task in which people listened to sensible conversations. What would people be likely to do in the "think about nothing in particular" baseline condition? If a good portion of the subjects actually lay there replaying the morning's conversation with a girlfriend, or running a recent lecture through their minds in preparation for midterms, there would be a good chance that important language areas of the brain would be involved. The activity in these areas would then become subtracted from the actual language condition, which might give the impression that certain key regions are not activated for language, simply because they were actually activated in *both* the critical language condition and the baseline comparison condition.

Instead of a "resting" baseline condition, researchers sometimes use a control condition that focuses the subject's attention on a specific task that is presumed to involve different computations than the condition of interest. For example, we might compare listening to words (linguistic input) with listening to single tones (non-linguistic input). The hope would be that the differences in activation (see **Figure 3.9**) would reflect the processing of spoken linguistic input as opposed to the processing of non-linguistic auditory input. But other unexpected differences might emerge. For example, it might be

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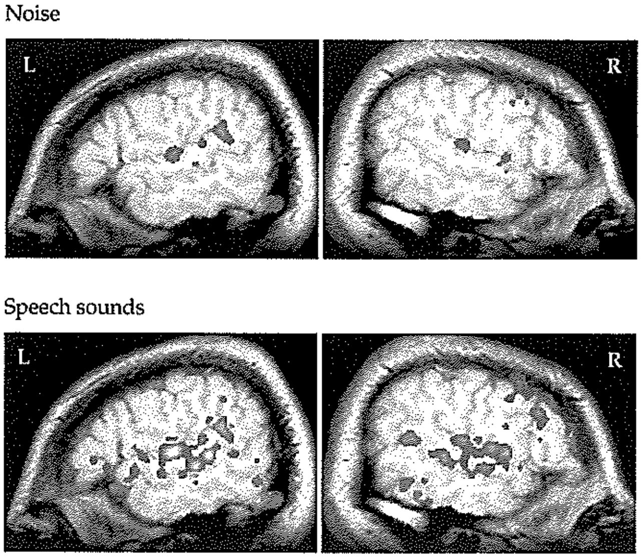

Noise

Speech sounds

**Figure 3.9** These fMRI scans are composites from several subjects that, when combined, indicate areas of peak activation. Pure tones or "noise" (top scans) activate a relatively small region of auditory cortex. When speech sounds are heard (lower two scans), strong activity appears in many areas of the dorsal and ventral auditory pathways. Both the left (L) and right (R) cerebral hemispheres are shown. (From Binder et al., 1994.)

### METHOD 3.2 *(continued)*

that the words are more complex examples of auditory stimuli and that they activate regions that are associated with processing complex sequences of sounds, whether linguistic or otherwise. Or, it may be that the words are more interesting and have an effect on brain areas that are linked to heightened attention. In this case, the results might show a difference in activation for a very large number of brain regions, even though only some of them are involved specifically in language.

To take one more example, let's say we compared listening to sentences with listening to musical melodies, based on the logic that both involve processing complex strings of auditory units but only one of them is linguistic. Let's also suppose that, unknown to us, processing melodies actually requires some of the same computations as unraveling the structure of spoken sentences, and involves some of the same areas of the brain. These regions would not show up in the results. The remaining areas that would be identified as being active in the language condition might well provide some answers to the question of which brain regions are devoted to language and not music. But what if we operated under the false assumption that language and music are fundamentally distinct in their computations and use of brain resources (other than what's required for basic auditory processing)? We might wrongly conclude that our results answered the question of which brain regions are recruited for the purpose of linguistic processing. By assuming too great a distinction between linguistic and musical processing, we might have missed out on identifying some important brain areas that are common to both types of stimuli.

With any luck, over a large number of studies and using a variety of comparison conditions, we'd start to get a clearer picture of how to isolate language-relevant brain regions. But in reading the results of any single study, it's important to realize that it's cutting corners to say, "This study revealed activation in region *X* for task *Y*." Statements like this should really be understood as an abbreviation for, "This study revealed greater activation in region *X* for task *Y* as compared with task *Z*." And this understanding should lead us to spend at least a little time thinking about the relationship between tasks *Y* and *Z*.

activating the same areas of the brain that would be engaged in non-linguistic tasks like silently reminiscing or looking at a photograph. The task itself may incite boredom or arousal, mental states that have certain brain activation patterns. A reasonable strategy for isolating the language areas is to come up with a comparison condition that's as similar as possible to the target stimulus except that it doesn't require language. The brain regions that show activity over and above the control task can then more plausibly be attributed to the linguistic aspect of the stimulus.

Now that neurolinguists are equipped with an anatomical map in one hand and imaging techniques for brain function in the other, what have we learned about language in the brain? Keeping in mind that there are literally thousands of studies out there, the next sections provide very broad outlines of two key conclusions.

### *Language function is distributed throughout the brain in complex networks*

Here's one way to think about the connection between brain regions and their function: we might conceive of important regions as dedicated processing centers, responsible for specific kinds of activities—for instance, visual processing, or language comprehension. A useful analogy might be to think of the regions as self-contained factories that take in raw material as input and produce certain products as output. Each factory has its own structural organization and sets of procedures that are independent from those in other factories, though some commonalities might crop up just because different factory operations settle on similar efficient solutions. This is an easy and intuitive way to think about brain localization, and it's probably made even more intuitive by the type of language that's often used in media reports of neuroimaging studies, with references to notions like "the pleasure center" or headlines like "Scientists Locate Sarcasm in the Brain."

But even some of the earliest proponents of brain localization argued that this picture of the brain as a collection of independent processing centers was overly simplistic. For instance, Brodmann himself doubted that any of the brain regions he identified would turn out to be encapsulated dedicated processors. In his 1909 seminal work, he warned:

> Mental faculties are notions used to designate extraordinarily involved complexes of elementary functions. . . . One cannot think of their taking place in any other way than through an infinitely complex and involved interaction and cooperation of numerous elementary activities. . . . Thus, we are dealing with a physiological process extending widely over the whole cortical surface and not a localized function within a specific region. We must therefore reject as a quite impossible psychological concept the idea that an intellectual faculty or a mental event or a spatial or temporal quality or any other complex, higher psychic function should be represented in a single circumscribed cortical zone, whether one calls this an "association centre" or "thought organ" or anything else.

In fact, if we turn to someone like Carl Wernicke, working early in the history of neuroscience, we see a similarly subtle view. Far from viewing Wernicke's area as something equivalent to the "language comprehension organ," Wernicke conceived of it as a critical piece in a larger network that linked information from different sensory modalities to information about the acoustic quality of words (see **Figure 3.10**).

Instead of thinking of the brain as an assortment of dedicated processing centers or independent factories, here's another possible scenario, one that is more in keeping with the speculations of Brodmann and Wernicke. Imagine the brain as a highly coordinated complex of commercial activity in which the makers of different products have arranged to share resources and their workers' expertise whenever possible. (For instance, the same factory space would handle the production of both fish sticks and chicken fingers, given that they rely on similar procedures. The packaging of many different kinds of goods might take place in another area, bringing together all kinds of frozen foods that go into boxes, including fish sticks, chicken fingers, miniature quiches, and hamburger patties.) In this industrial complex, the production of a specific

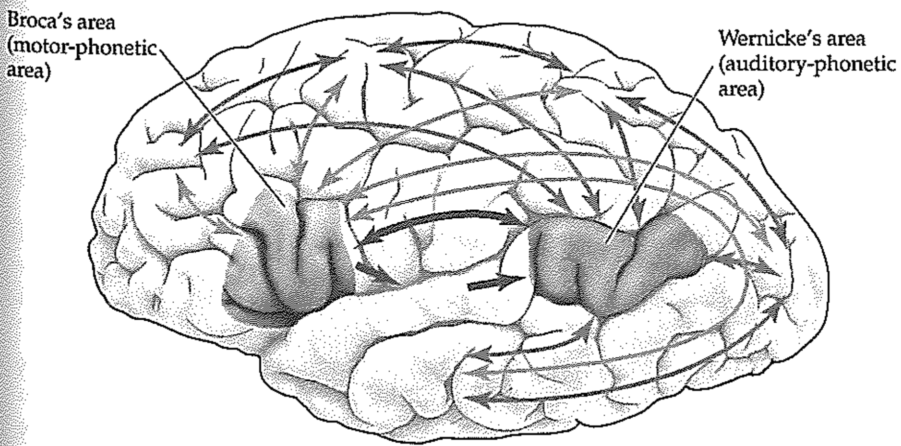


**Figure 3.10** Wernicke's view of language involved a broadly distributed network. Thick red arrows connect the "motor-phonetic" or Broca's area and the "auditory-phonetic" or Wernicke's area. The blue arrows show connections between Wernicke's area and areas that store non-verbal information in "acoustic," "visual," "tactile," and "motor imagery" areas. The orange arrows represent connections between Broca's area and these various sensory areas. The green arrows show connections among the various sensory areas outside of the language network. (After Ross, 2010.)

product wouldn't take place within an isolated factory—instead, its trajectory from start to finish could be described as a path through the complex, making use of whichever resources were suitable for the production process. Some areas within the complex might be highly specialized, with a very small number of specific products (or perhaps even just one type of product) moving through them, while others would perform general tasks that apply to a great number of different products. One consequence of this kind of arrangement would be that products might have to travel large distances from one area of the complex to another, depending on what specific operations they needed to undergo.

From the very earliest work applying brain imaging to the study of language, results have lined up better with this second view of distributed brain function than with the first view of brain regions as dedicated processing centers. In the rest of this section, I'll touch on just a small subset of relevant examples.

In 1978, Bo Larsen and colleagues used a technique that was a precursor to PET and fMRI to identify the regions of the brain that were active while subjects listened to speech, as opposed to the regions that were active while "resting." Surprisingly, in the language-listening task, they found activity not just in Broca's and Wernicke's areas, but also throughout much of both the left and right hemispheres. They concluded that conversation was "likely to involve not only the cortical areas of importance for speech, but practically the whole brain, the left as well as the right side."

The fact that language-related functions are scattered throughout the brain is a testament to the great variety of separate tasks that need to be accomplished in the course of regular, daily language use. Many of the right-hemisphere functions seem to be quite different and complementary to those in the left, perhaps focusing on taking into account how something was said rather than decoding what was said. For example, the processing of information about intonation appears to be mainly housed in the right hemisphere (e.g., Ross & Monnot, 2008). The right hemisphere may also play an important role in how individual sentences are linked together into a coherent story or discourse (e.g., St. George et al., 1999).

The spatial distribution of language in the brain, though, isn't just due to the fact that a great variety of separate tasks are involved. Some of the diffusion also comes from the fact that language is entangled with non-linguistic knowledge. One of the most striking demonstrations of this is the pattern of brain activity that researchers see when they study the recognition of words. It doesn't seem unreasonable, as a first guess, to propose that word recognition might be associated with a certain pattern of brain activity—perhaps there's a location that corresponds to a "mental dictionary," or a general connection path between a "sounds" region of the brain and a "meaning" area. But in fact, you can get quite different patterns of activation for the following three categories of words:

| (A) | (B) | (C) |
|---|---|---|
| kick | type | lick |
| step | throw | speak |
| walk | write | bite |
| tiptoe | grasp | smile |
| jump | poke | chew |

Did you figure out what each category has in common? The words in category A refer to actions that involve the feet or legs; the words in category B name actions that require the use of fingers, hands, or arms; and the words in category

C describe actions accomplished via movements of the mouth and face. As demonstrated by Olaf Hauk and colleagues (2004), simply *reading* words from these categories activates some of the same brain regions involved in actually carrying out the movements, and reading words from different categories activates different brain regions (reading *kick* activates some of the brain regions involved in moving the feet, etc.; see **Figure 3.11**). Some of the more typical "language-y" areas are engaged as well, but, as Wernicke so astutely predicted at the dawn of modern neuroscience, fMRI data provide visible evidence that the language representations are connected with information in various other regions of the brain that are responsible for storing information about movement and the senses.

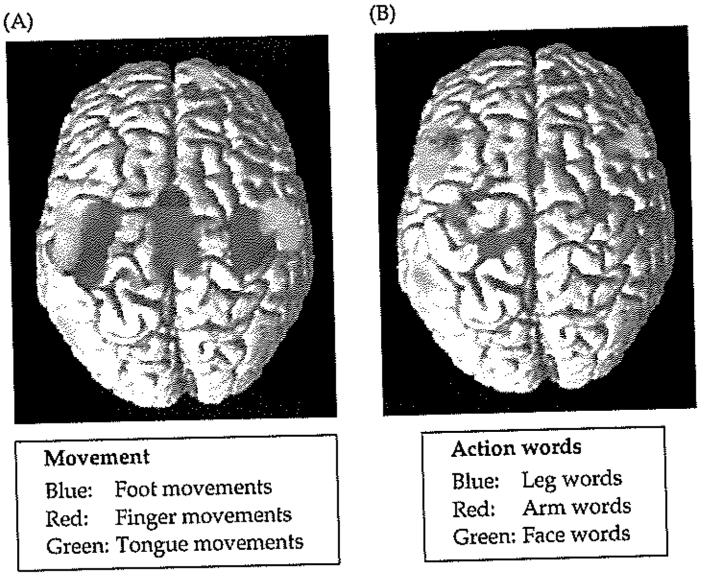


**Figure 3.11** Results from a study of action words. (A) Activation of brain areas following instructions to move particular parts of the body. (B) Activation of brain areas during silent reading of action words involving three different parts of the body. In a comparison (baseline) condition, subjects saw meaningless rows of hatch marks, averaging the same length as the action words. (From Hauk et al., 2004.)

## The functional neuroanatomy of language

Thinking about language function in terms of many distinct (but often overlapping) networks can help explain some otherwise mystifying data. For example, some patients with brain lesions do poorly on speech perception tests that require them to discriminate between two different syllables. You might predict that this would lead to great difficulty in recognizing words as well—but, while that's true for many patients, it's not necessarily the case. Some patients with poor speech perception skills are easily able to recognize the meanings of words, though they often have a great deal of trouble with language *production*. Conversely, there are other patients who have trouble recognizing words, but pass tests of basic speech perception with flying colors. It seems that it's possible to find cases of double dissociation between the processing of sequences of speech sounds and the recognition of words. What could possibly be going on, since (presumably) you can't easily figure out what a word is without having processed its individual sounds?

Greg Hickok and David Poeppel (2007) have argued that these puzzling findings start to make more sense if you think of the two tasks as belonging to different language-related networks. According to Hickok and Poeppel, word recognition recruits a network that maps speech input onto representations of meaning. Performing tasks like identifying individual syllables, on the other hand, leans more heavily on a different network that maps the acoustic information about sounds onto the articulatory gestures that produce them (this would be the kind of mapping that babies are learning during the babbling stage, when they spend countless hours uttering strings of meaningless sounds, as described in Chapter 2.) This would explain why trouble with simple speech perception tasks can be more directly connected to impairments in language *production* than to difficulties in understanding the meanings of words.

It might seem weird that knowledge of speech sounds would split apart into two separate networks like this. But other modalities show similar dissociations. It's now well known that visual recognition of physical objects fractures into knowledge of *what* objects are and of *how* they are to be used. This can lead to bizarre cases in which, for example, a brain-damaged patient is unable to visually recognize what a comb is or describe its purpose, but can easily demonstrate how to use it. It's more intuitive to think of our knowledge of objects (or sounds) as falling into one bin, but in fact, there's strong

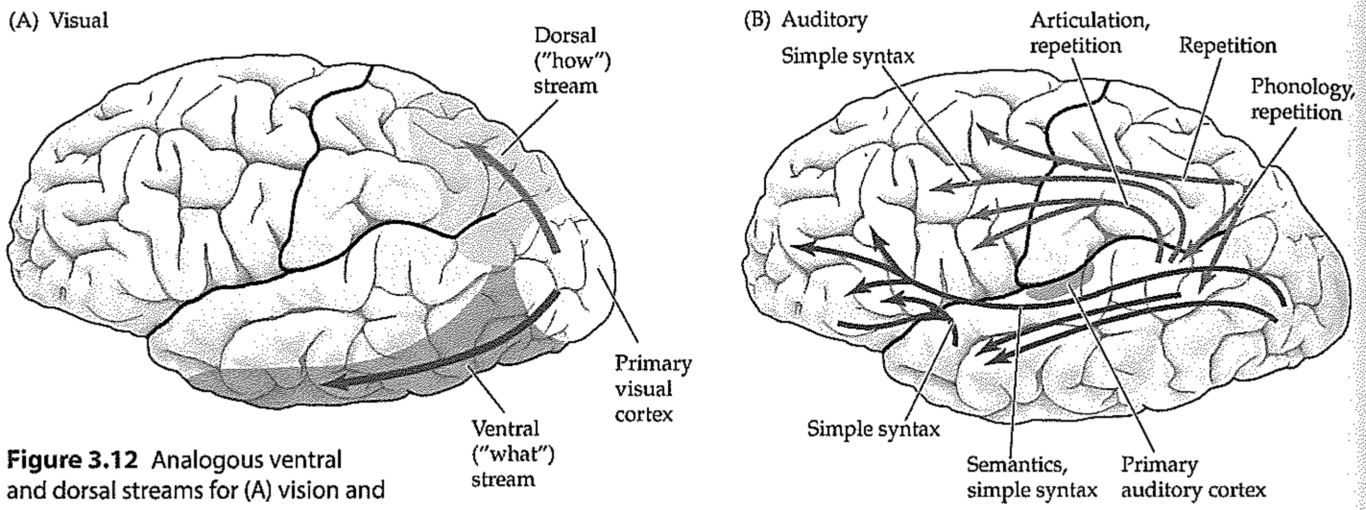


**Figure 3.12** Analogous ventral and dorsal streams for (A) vision and (B) language in the left hemisphere of the brain. (B adapted from Gierhan 2013.)

evidence that separate knowledge streams exist for processing "what" and "how" information.

The separation of distinct "what" and "how" networks in the brain seems to be a basic way of organizing knowledge across a number of different domains, governing not just vision, but auditory perception and memory as well. Memory researchers, for instance, have long distinguished between declarative and procedural memory. **Declarative memory** refers to memory for facts and events (whether real or fictional) and includes bits of information such as the date on which World War I began, the names of Snow White's seven dwarves, and the object of your first crush. **Procedural memory**, on the other hand, refers to memory for actions, such as how to thread a sewing machine or play your favorite guitar riff. If you've ever forgotten a familiar phone number, only to be able to dial it correctly when given a keypad, then you've directly experienced the disconnect that can happen between the two kinds of memory.

There's now considerable evidence that language, too, is organized in two streams, and that these streams have clearly distinct locations in the brain. As with vision, processing the first type of information (the "what" knowledge) is organized into a network known as the **ventral stream**; the second type of information (the "how" knowledge) takes place in the **dorsal stream** (see **Figure 3.12** and **Box 3.5**). A good deal of research is being conducted with the aim of identifying exactly what kind of information is shuttled along each highway (a 2013 review by Sarah Gierhan provides an overview). The dorsal pathways seem to be involved in information that's relevant for the detailed processing of sounds, for the planning of articulation, and for the repetition of words. The ventral pathways specialize in information about word meanings; damage to these connections, for example, can lead to trouble in understanding the meanings of words, or in retrieving words from memory. Both networks appear to be involved in the processing of syntactic information, though some researchers have suggested that each system is responsible for different kinds of syntactic information, with the processing of very complex structures taking place along the dorsal network.

Much of the emerging evidence supporting the existence of dorsal and ventral pathways is the result of new approaches and techniques that allow researchers to take the next step beyond simply identifying which regions of the brain are active during language tasks. They can now also investigate the ways in which the various language-related regions of the brain are connected to each other by

**declarative memory** Memory for facts and events (whether real or fictional) that can be spoken of ("declared").

**procedural memory** Memory for physical actions and sequences of actions.

**ventral stream** Theoretical "knowledge stream" of ventral neural connections (i.e., located in the lower portion of the brain) that process knowledge about "what."

**dorsal stream** Theoretical "knowledge stream" of dorsal neural connections (i.e., located in the upper portion of the brain) that process knowledge about "how."

long bundles of neural fibers (*axons;* see Section 3.4) collectively called **white matter**. White matter tracts act as the brain's road networks, allowing products from one processing area to be shuttled to another area for further processing or packaging. (Fun fact: The average 20-year-old human possesses between 150,000 and 175,000 kilometers of white matter fibers, as estimated by Lisbeth Marner and her colleagues in 2003. That's a lot of road.) White matter fiber tracts can be visualized in the living brain by using **diffusion magnetic resonance imaging (dMRI)**, which tracks how water molecules diffuse through the brain. Since water dif-

**white matter** Bundles of neural tissue (axons) that act as the brain's information network, allowing products (signaling molecules) from one processing area to be shuttled to another area for further processing.

**diffusion magnetic resonance imaging (dMRI)** Neuroimaging technique that tracks how water molecules are diffused in the brain, providing a view of the brain's "white matter highway."

## BOX 3.5

## The functional neuroanatomy of language

The language areas of the cerebral cortex (the outer layer of neural tissue that covers the cerebral hemispheres) are diagrammed in **Figure 3.13**.

The **STG** (superior temporal gyrus) and the posterior portion of the **STS** (superior temporal sulcus) are involved in the phonological stages of spoken-word recognition—for example, in distinguishing between the important sounds in *bear* versus *pear*. This function seems to be bilaterally organized. That is, damage to only the left hemisphere does not result in great difficulties in processing the details of sound, but damage to both hemispheres (bilateral damage) results in "word deafness," in which hearing is preserved but understanding of speech is badly impaired.

The anterior temporal lobe region labeled **ATL** is involved in accessing and integrating semantic knowledge across modalities, and within a syntactic structure. Damage to this area leads to difficulties in understanding complex or ambiguous sentences. Also in the anterior temporal lobe, the **MTG** (middle temporal gyrus), **ITG** (inferior temporal gyrus), and anterior portions of the **STS** play a role in mapping sound to meaning and are also involved in accessing the meaning of written words. The representation of the meanings of words is widely distributed throughout the cerebral cortex (see Figure 3.11), but some researchers have argued that there is a more organized "hub" for word meanings in the anterior temporal region.

The left dorsal **STG** and **SMG** (supramarginal gyrus), along with the primary auditory cortex (**Aud**) and areas of the primary **motor cortex**, play a role in speech production, which involves integrating auditory information with a set of motor sequences for speech. Unlike speech perception, speech production seems to be heavily lateralized in the left hemisphere.

The **Spt** (Sylvian parietal temporal) region may play a role in sensory-motor integration for the vocal tract,

*Continued on next page*

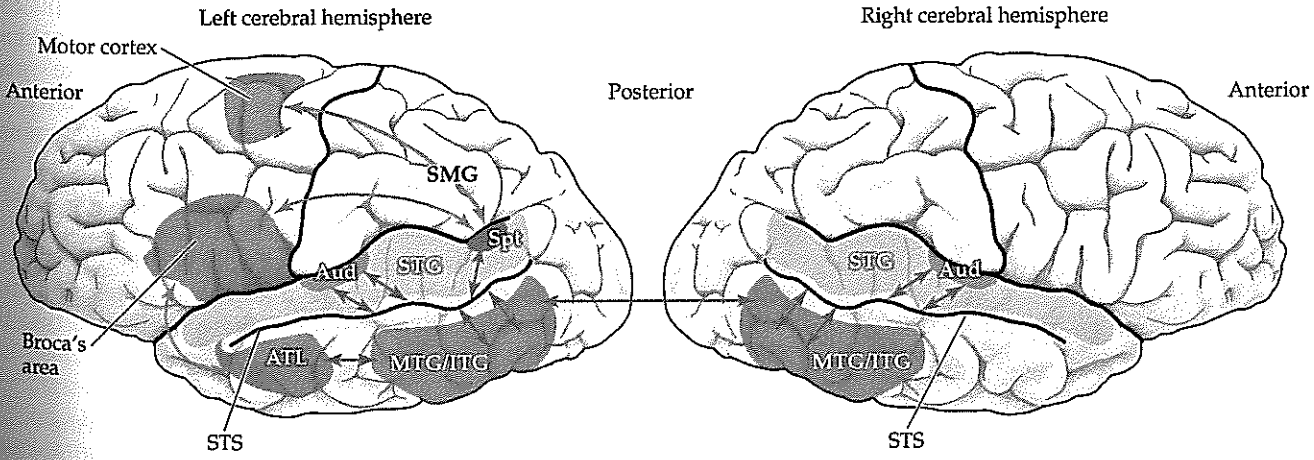


**Figure 3.13** This contemporary view of areas of the brain that contribute to language function, as organized into dorsal (green arrows) and ventral networks (red arrows; see Figure 3.12). Note that the networks extend into the right as well as the left cerebral hemisphere, although the left-hemisphere structures predominate. (Adapted from Hickok, 2009.)

BOX 3.5 *(continued)*

including "auditory imagery" of speech and non-speech vocal sounds (for example, humming music), whether the task involves producing sounds out loud or simply imagining them. This region shows heightened activity if auditory feedback from speech is disrupted (for instance, by delays). It is also likely involved in short-term verbal memory, which keeps sound-based information about words active in memory (for example, mentally "rehearsing" a phone number so you don't forget it before you get a chance to dial it). This region also supports the learning of new, unfamiliar words.

**Broca's area** (Brodmann areas 44 and 45) supports the production and understanding of syntactic structure.

In addition to the language areas of the cerebral cortex shown in Figure 3.13, language may also involve subcortical (internal) areas of the brain. For example, the **basal ganglia**, a collection of structures deep inside the brain (see **Figure 3.14**), have a key role in regulating bodily movement but also appear to be connected to the dorsal auditory stream. Some researchers argue that the basal ganglia play an important role in the sequencing of sounds and syntactic units.

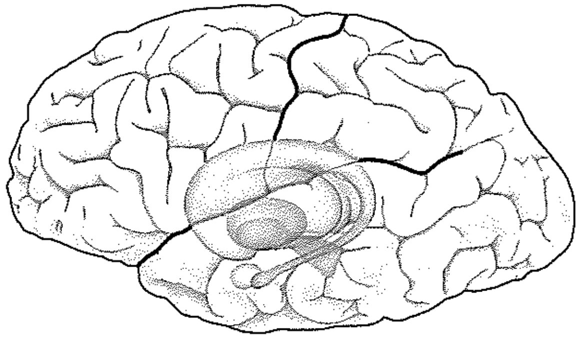


**Figure 3.14** The basal ganglia, located deep within the forebrain, consist of several brain nuclei (clusters of anatomically discrete neurons, seen here in different shades of blue and lavender) and appear to have functions in the language pathway as well as their better-known functions in the motor pathway.

fuses in a direction that runs parallel to the white matter fiber bundles, dMRI provides a view of the brain's "white matter road" (see **Figure 3.15**) and, crucially, some insight into how information moves between various regions of the brain—including the dorsal and ventral information processing "highways."

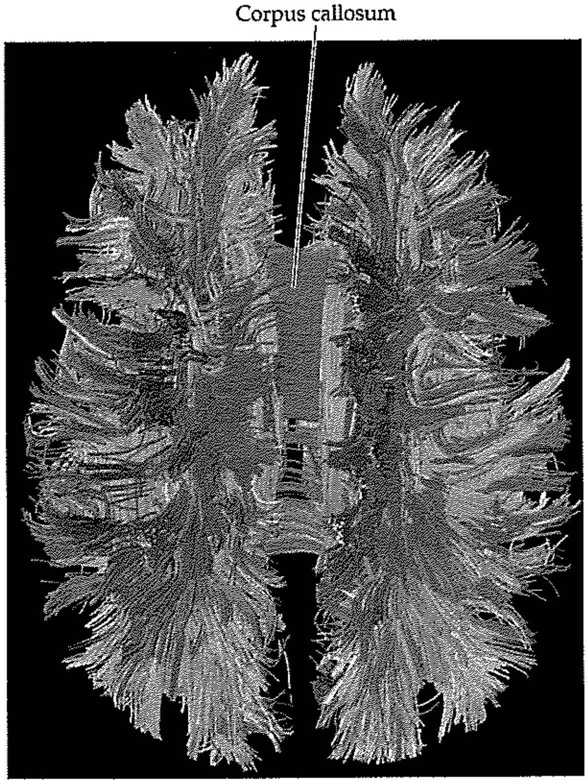


**Figure 3.15** A view of the brain using dMRI, which tracks the movement of water molecules through the brain. Water diffuses in a manner that parallels the white matter tracts that carry neural signals. This imaging technique can provide insights into how information moves between various regions of the brain. (Courtesy of Patric Hagmann.)

## *Brain organization for language is both specialized and flexible*

Broca's area, which is implicated in language production, is conveniently located next to the part of the motor cortex that controls movement of the mouth and lips, while Wernicke's area, which is important for comprehension, sits next door to the auditory cortex (see **Figure 3.16**). This makes sense, as there would likely be many connections between these adjacent areas. But not all language is spoken. Sign languages involve making movements with the hands rather than with the tongue and lips (though much of the face can be heavily involved); no hearing is necessary, with comprehension relying instead on visual-spatial processes. So here's a trick question: Where would you find the language-related networks for people who grew up with a sign language as their native language? Would Broca's and Wernicke's areas be involved? Or would language establish its base camps in other regions? A logical place to look for this hypothetical "sign language network" might be near the part of the motor cortex that controls hand movements, or over in the right hemisphere, which takes on a good portion of visual-spatial processing.

In order to think about this question, let's revisit our metaphor of the brain as a complex commercial network that makes many different kinds of products. Having an area like Wernicke's next to the auditory cortex is a lot like setting up a fish stick factory near a fishing port—sensible, as the main ingredients don't need to travel far in order to get to the processing plant. But what if, instead of making fish sticks, we decided to make chicken fingers? The ingredients are different, but it turns out that the machinery needed is very similar, as are the various steps in the production process. While it might make sense to build our chicken finger factory near a chicken farm, what if there's already a facility in place near a fishing port that's ideally set up for making products like fish sticks and chicken fingers? Even though it might require shipping the raw ingredients over a greater distance, it might still make more sense to use that facility than to build a whole new facility. So, one way to think about the question of localization of brain function is like this: does the brain's organization reflect mostly the raw ingredients that it uses (spoken sounds versus hand movements), or does it specialize for the various processes (that is, the specific computations) that the raw ingredients have to undergo?

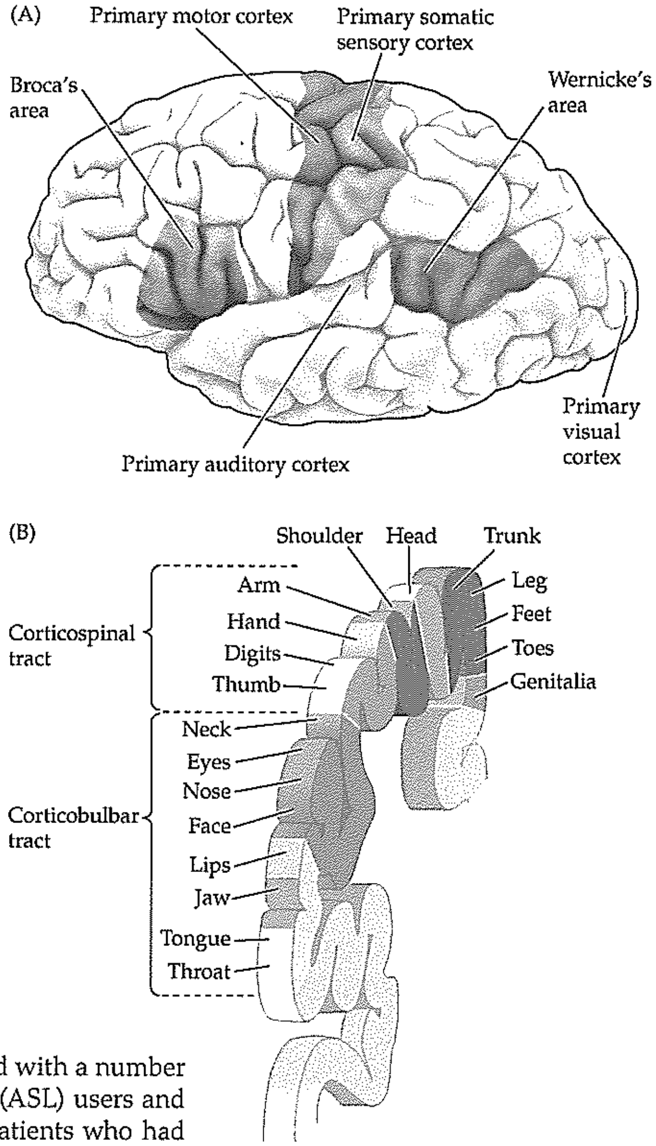
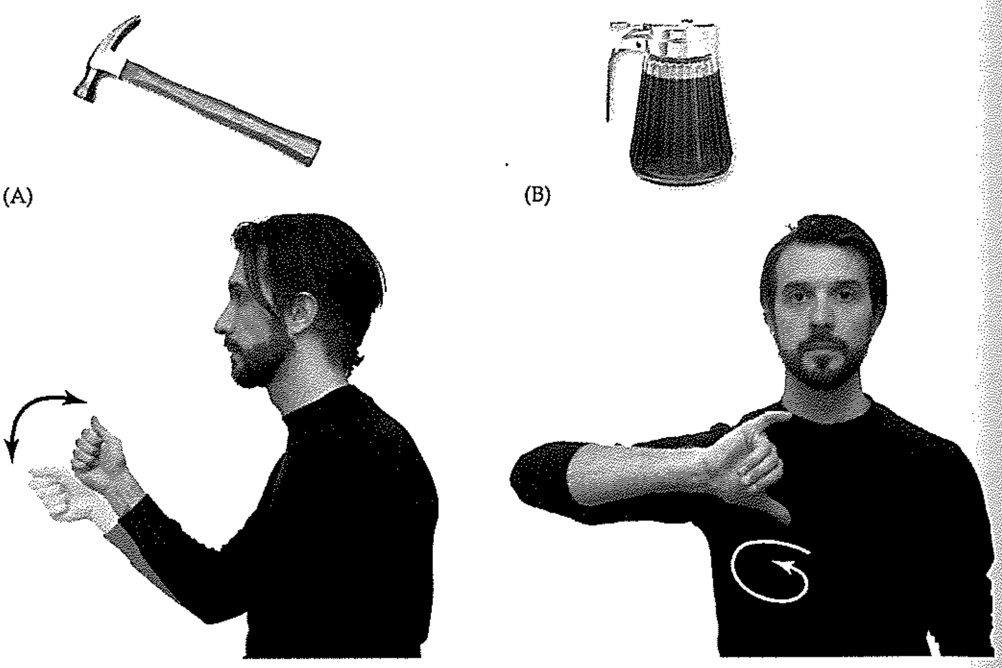


**Figure 3.16** (A) This drawing illustrates the proximity of the motor cortex to Broca's area, and of the auditory cortex to Wernicke's area. (B) A schematic illustration of the organization of the primary motor cortex. The areas that control movements of the mouth and lips are located near Broca's area, while the areas controlling movements of the hands, arms, and fingers are more distant.

The answer is that, at least much of the time, the brain specializes for processing rather than for the ingredients. This can be seen from a number of studies of sign language users. For example, Greg Hickok and colleagues (2001) worked with a number of patients with aphasia who were American Sign Language (ASL) users and found that, just like hearing folks, there were deaf aphasic patients who had trouble producing signs but could comprehend them reasonably well, while others could produce signs but had trouble understanding them. The deaf patients had brain damage in exactly the areas usually found for aphasic hearing patients—in the areas known as Broca's and Wernicke's, respectively.

Evidence from imaging confirms that the brain organization of ASL signers looks a lot like that of speakers of sound-based languages despite the fact that a completely different modality is being used (for a review, see MacSweeney et al., 2008). This is interesting because in the last chapter, we saw that when gesture is used *linguistically* by homesigners and inventors of new sign languages, it has deeply different properties from pantomime gesture—a fact that had been lost on hearing observers for many years. The distinction between linguistic and non-linguistic gesture also shows up in brain-imaging studies, as found by Karen Emmorey and her colleagues (2011) when they compared brain activation patterns for ASL signs with those for pantomime gestures. To people who don't know ASL, signs can sometimes *look* like pantomime because a number of signs have their origins in a pantomimed gesture that became conventionalized. For example, the ASL signs used to communicate the concepts of hammering or of pouring syrup are a lot like what you'd do if you were asked to

**Figure 3.17** Examples of ASL verbs produced in response to the pictured objects.



TO-HAMMER

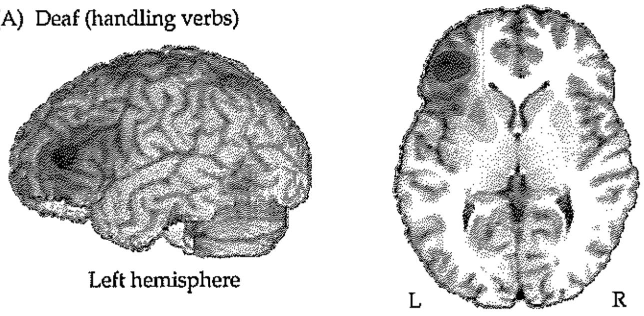
POUR-SYRUP

pantomime the actions rather than convey them linguistically (see **Figure 3.17**). Emmorey and her colleagues decided to look specifically at iconic signs like these, in order to see whether producing them would activate different brain regions than would pantomiming gestures, even though the hand motions for the two are actually very similar.

To elicit a linguistic sign, the researchers showed native ASL signers a picture of an object, such as a hammer or a bottle of syrup, and asked the signers to generate a verb related to that object. If pantomime gestures were being elicited, subjects were asked to gesture to show how they would use that object. **Figure 3.18** shows data from brain scans for ASL signers producing verbs and from hearing subjects who were gesturing rather than using language. As you can see, the patterns of activation are quite different; the ASL verbs resulted in more activity in the frontal lobe, home of Broca's area, while pantomime gestures triggered more activity in the parietal lobe.

Sign language studies show that when it comes to brain localization, it's not just the raw ingredients of your language that matter; it's also what you do with them. Language networks in the brain readily adapt to a slew of different materials that could be used for linguistic purposes. This is apparent in spoken languages too. For example, lan-

(A) Deaf (handling verbs)



(B) Hearing ("handling verbs" pantomime)

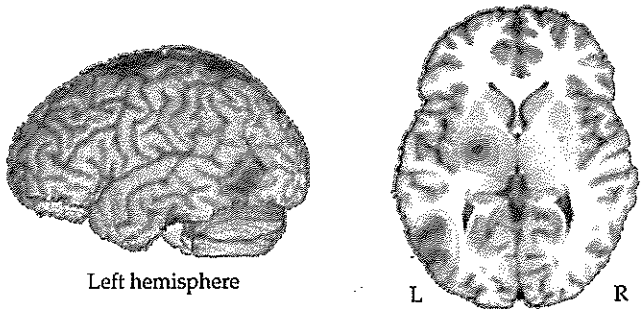


**Figure 3.18** Averaged data for (A) brains scans of deaf subjects producing ASL signs and (B) hearing subjects producing pantomime gestures in response to the same stimuli. These scans plot comparisons with a baseline condition in which subjects saw pictures of objects and gave a thumbs-up to indicate that the objects could be manually handled or waved their hands to indicate that they couldn't. (From Emmorey et al., 2011.)