

COGNITIVE PSYCHOLOGY

and Its Implications

NINTH EDITION



John R. Anderson

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Description

The front cover shows a photo that highlights ultra wide view of a bridge that crosses a lake with a backdrop of sun rays shining bright from

behind a range of mountains. A person walks on the bridge toward the mountain. On the top, the title of the book reads, Cognitive Psychology and Its Implications; the name of the author at the bottom reads, John R. Anderson.

Cognitive Psychology and Its Implications



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Cognitive Psychology and Its Implications

Ninth Edition

John R. Anderson

Carnegie Mellon University



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JOHN ROBERT ANDERSON is Richard King Mellon Professor of Psychology and Computer Science at Carnegie Mellon University. He is known for developing ACT-R, the most widely used cognitive architecture in cognitive science. Anderson was also an early leader in research on intelligent tutoring systems: Computer systems based on his cognitive tutors currently teach mathematics to about 500,000 children in U.S. schools. He has served as president of the Cognitive Science Society and has been elected to the American Academy of

Arts and Sciences, the National Academy of Sciences, and the American Philosophical Society. He has received numerous scientific awards, including the American Psychological Association's Distinguished Scientific Career Award, the David E. Rumelhart Prize for Contributions to the Formal Analysis of Human Cognition, the inaugural Dr. A. H. Heineken Prize for Cognitive Science, and the Atkinson Prize in Psychological and Cognitive Science from the National Academy of Sciences.

To Gordon Bower for 50 years of inspiration

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Preface



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Description

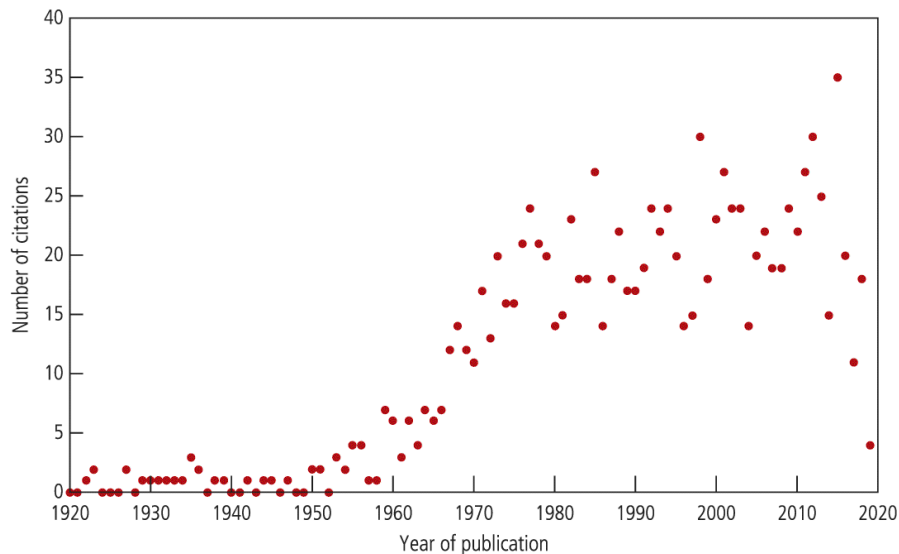
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Writing this preface is an occasion to reflect on where the field of cognitive psychology has been, where it is, where it is going, and how all this is manifested in the ninth edition of *Cognitive Psychology and Its Implications*. The figure below provides one measure of how research over the years has served to shape my conception of cognitive psychology—a conception that I think is shared by many researchers in the field. The figure shows the number of works cited in this textbook that were published in each of the last 100 years. I

have not felt the need to throw out references to classic studies that still serve their purpose, and so the figure partially reflects four periods in the evolution of cognitive psychology:

1. Before the end of World War II, behaviorism dominated psychology and there was relatively little interest in human cognition. The few citations to papers published in this period are mainly references to classic studies that still serve their purpose.
2. After 1950, the postwar generation of researchers broke the behaviorist grip on psychology and started the cognitive revolution. The growing number of citations during this time reflects the rise of a new way of studying and understanding the human mind.
3. At about the time when the first edition of this textbook was published, in 1980, the framework that the pioneers had established was there for me to start with, and I was able to organize it into the coherent structure that appeared in the first edition. Starting in 1980 the number of citations basically levels off.
4. A major development in the field that really began to establish itself in the 1990s is hidden beneath the relatively stable level of citations in the figure. Early research had focused on behavioral measures because studying what was going on in the human brain seemed ethically impossible. However, new techniques in neural imaging arose in the 1990s that allowed us to relate early behavioral research to brain activity. This neuroscience research

has been complemented by cognitive research on animals, particularly primates.



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Citations to Works Published in Each Year, 1920–2019. Cognition-related research lay dormant until the middle of the twentieth century and then expanded enormously, with the coming of the cognitive revolution. The graph shows that this book contains a total of about 20 citations of works published in the years 1910–1949, compared with a total of about 1,000 citations of works published since 1950.

Description

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While it is easy to characterize how the field of cognitive psychology has gotten to where it is today, it is a challenge to see where it is going. There are a number of developments in the field (described in this new edition of the text) that make its future uncertain: The field is rethinking the question of whether it wants to be a science of the brain or a science of the mind and is trying to determine how these two goals relate to one another. New developments in artificial intelligence are changing both the framework in which we think about human intelligence and the tools for studying it. The field is debating what the best statistical and research methodologies are for uncovering reliable and important findings. While I am not sure what the future of cognitive psychology will be, the goal of this new edition is to capture the current state of the field.

New in the Ninth Edition

Writing a new edition always means making decisions about what to update, what to add, and what to delete. There are a number of new topics in this textbook, largely reflecting new developments in the field, but in some cases picking up on things that were missed in earlier editions. These are the major new additions:

Chapter 1: A new section on the increased centrality of cognitive neuroscience.

Chapter 2: New material on deep convolutional networks and their implications for our understanding of human vision.

Chapter 3: A new section on inattentional blindness.

Chapter 4: A new section on individual differences in visual imagery.

Chapter 5: A new discussion of how research using body cameras has enabled detailed study of our memory for everyday experiences.

Chapter 6: A new section on spacing effects.

Chapter 7: New material on eyewitness testimony.

Chapter 8: A new section on the decision to give up on a problem-solving attempt.

Chapter 9: A new section on the role of talent versus deliberate practice in the development of expertise.

Chapter 10: A new section on causal reasoning.

Chapter 11: A new section on choosing among multiple alternatives.

Chapter 14: New material on cognitive and neural correlates of intelligence.

In addition, the number of Implications boxes has nearly doubled, enabling me to place research in cognitive psychology in a larger

context. These are the new Implications boxes:

Chapter 1: The Replicability Crisis

Chapter 2: Developments in Face-Recognition Software

Chapter 3: Cell Phones and Distraction

Chapter 4: Spatial Skills and STEM Education

Chapter 7: Is Forgetting Adaptive?

Chapter 8: When Humans Are Better at Solving Problems Than Computers

Chapter 11: What Can We Believe with High Confidence?

Chapter 12: Does Bilingualism Confer a Cognitive Advantage?

Chapter 13: Nonverbal Communication

Chapter 14: Is There a Relationship Between Age and Job Performance?

The Structure of This Book: A Note to Instructors

Instructors will use this textbook in their own ways, but when I teach from this book, I impose the following structure on it:

- The first chapter prepares students for understanding subsequent chapters, and the last chapter reflects on how all the pieces fit together in our picture of human cognition and intelligence.
- The meat of the textbook is the middle 12 chapters, which naturally organize themselves into 6 thematic pairs: perception and attention ([Chapters 2](#) and [3](#)), knowledge representation ([Chapters 4](#) and [5](#)), memory ([Chapters 6](#) and [7](#)), problem solving ([Chapters 8](#) and [9](#)), reasoning and decision making ([Chapters 10](#) and [11](#)), and language ([Chapters 12](#) and [13](#)).
- There is a major break between the first three pairs and the last three pairs. As I tell my class at that point: “Most of what we have discussed up to this point is true of all primates. Most of what we are going to talk about now is only true of humans.”

Teaching and Learning Resources

Instructor resources accompanying this ninth edition of *Cognitive Psychology and Its Implications* include an instructor's resource manual, a computerized test bank, lecture slides, and illustration slides (all slides can be used as they are or customized to fit course needs).

- The **instructor's resource manual** features a chapter summary for each text chapter, highlighting key concepts and research studies; a list of learning objectives; online resources; and suggested readings, videos, and in-class discussion prompts. Resources are organized by topic, based on the chapter section headings.
- The **test bank** contains a mix of 100 essay, multiple choice, and short answer questions for each chapter. All questions are keyed to the American Psychological Association's goals for the undergraduate psychology major and Bloom's taxonomy. There are a wide variety of applied, conceptual, and factual questions, and each question is keyed to the topic and to the page in the text where the answer can be found.
- The **lecture slides** focus on key concepts and themes from the text and feature tables, graphs, and figures.
- The **illustration slides** include all the figures, photos, and tables featured in the text.

Acknowledgments

I appreciate the efforts of my editor Sarah Berger in organizing the reviews that provided much guidance on the needed revisions and her efforts in organizing the many aspects of ushering a new edition into publication. I appreciate the hard work of the developmental editor, Len Neufeld. This is the second edition he has worked on, and each time the book is again better in terms of getting the material across in an understandable and accurate form.

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Chapter 1 The Science of Cognition



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Our species is called *Homo sapiens*, or “human, the wise,” reflecting the general belief that our superior thought processes are what distinguish us from other animals. Today we all know that the brain is the organ of the human mind, but the connection between the brain and the mind was not always known. For instance, in a colossal misassociation, the Greek philosopher Aristotle localized the mind in the heart. He thought the function of the brain was to cool the blood. [Cognitive psychology](#) is the science of how the mind is organized to produce intelligent thought and how the mind is realized in the brain.

This chapter introduces fundamental concepts that set the stage for the rest of the book by addressing the following questions:

- Why do people study cognitive psychology?
- Where and when did cognitive psychology originate?
- How is the mind realized in the body?

How do the cells in the brain process information?

What parts of the brain are responsible for different functions?

What are the methods for studying the brain?

Motivations for Studying Cognitive Psychology

Intellectual Curiosity

As with any scientific inquiry, the thirst for knowledge provides much of the impetus to study cognitive psychology. In this respect, the cognitive psychologist is like the tinkerer who wants to know how a clock works. The human mind is particularly fascinating: It displays a remarkable intelligence and ability to adapt. Yet we are often unaware of the extraordinary aspects of human cognition. Just as when watching a live broadcast of a distant news event we rarely consider the sophisticated technologies that make the broadcast possible, we also rarely think about the sophisticated mental processes that enable us to understand that news event. Cognitive psychologists strive to understand the mechanisms that make such intellectual sophistication possible.

The inner workings of the human mind are far more intricate than the most complicated systems of modern technology. For over half a century, researchers in the field of [artificial intelligence \(AI\)](#) have been attempting to develop programs that will enable computers to display intelligent behavior. There have been some notable successes, such as IBM's Watson ([Ferrucci et al., 2010](#)), which defeated human contestants on *Jeopardy* in 2011, and DeepMind's AlphaGo program ([Silver et al., 2017](#)), which beat the world

champion Go player in 2017. Still, these are specialized programs, and no artificial intelligence system has yet come forward that matches humans in generalized [intelligence](#), with human flexibility in recalling facts, solving problems, reasoning, learning, and using language.

There does not appear to be anything magical about human intelligence that would make it impossible to model in a computer. Scientific discovery, for instance, is often thought of as the ultimate accomplishment of human intelligence: Scientists supposedly make great leaps of intuition to explain extremely puzzling sets of data. Formulating a novel scientific theory is supposed to require both great creativity and special deductive powers. But is this actually the case? Herbert Simon, who won the 1978 Nobel Prize for his theoretical work in economics, spent the last 40 years of his life studying cognitive psychology. Among other things, he focused on the intellectual accomplishments involved in “doing” science. He and his colleagues ([Langley, Simon, Bradshaw, & Zytkow, 1987](#)) built computer programs to simulate the problem-solving activities involved in such scientific feats as Kepler’s discovery of the laws of planetary motion and Ohm’s development of his law for electric circuits. Simon also examined the processes involved in his own now-famous scientific discoveries ([Simon, 1989](#)). In all cases, he found that the methods of scientific discovery could be explained in terms of the basic cognitive processes that we study in cognitive psychology. He wrote that many of these activities are just well-

understood problem-solving processes (see [Chapters 8](#) and [9](#)). He says:

Moreover, the insight that is supposed to be required for such work as discovery turns out to be synonymous with the familiar process of recognition; and other terms commonly used in the discussion of creative work — such terms as “judgment,” “creativity,” or even “genius” — appear to be wholly dispensable or to be definable, as insight is, in terms of mundane and well-understood concepts. ([Simon, 1989, p. 376](#))

In other words, a detailed look reveals that even what are often described as the brilliant results of human genius are produced by basic cognitive processes operating together in complex ways to produce those results.¹ Most of this book will be devoted to describing what we know about these basic processes.

Great feats of intelligence, such as scientific discovery, are the result of basic cognitive processes.

Implications for Other Fields

Students and researchers interested in other areas of psychology or social science have another reason for following developments in cognitive psychology. The basic mechanisms governing human thought are important in understanding the types of behavior studied by other social sciences. For example, an appreciation of how humans think is important to understanding why certain thought malfunctions occur (clinical psychology), how people behave with

other individuals or in groups (social psychology), how persuasion works (political science), how economic decisions are made (economics), why certain ways of organizing groups are more effective and stable than others (sociology), and why natural languages have certain features (linguistics). Cognitive psychology is thus the foundation on which other social sciences stand, in the same way that physics is the foundation for the other physical sciences.

Nonetheless, much social science has developed without grounding in cognitive psychology, for two related reasons. First, the field of cognitive psychology is relatively new, having really only begun in the 1950s. Second, researchers in other areas of social science have managed to find other ways to explain the phenomena in which they are interested. An interesting case in point is economics. Neoclassical economics, which dominated the last century, tried to predict the behavior of markets while completely ignoring the cognitive processes of individuals. It simply assumed that individuals behaved in ways to maximize their wealth. However, the recently developed field of behavioral economics acknowledges that the behavior of markets is affected by the flawed decision-making processes of individuals — for example, people are willing to pay more for something when they use a credit card than when they use cash ([Simester & Drazen, 2001](#)). In recognition of the importance of the psychology of decision making to economics, the cognitive psychologist Daniel Kahneman was awarded the Nobel Prize for economics in 2002.

Cognitive psychology is the foundation for many other areas of social science.

Practical Applications

Practical applications of the field constitute another key incentive for the study of cognitive psychology ([Groome & Eysenck, 2016](#)). If we really understood how people acquire knowledge and intellectual skills and how they perform feats of intelligence, then we would be able to improve their intellectual training and performance accordingly.

While future applications of cognitive psychology hold great promise ([Klatzky, 2009](#)), there are a number of current successful applications. For instance, there has been a long history of research on the reliability of eyewitness testimony (e.g., [Wells, Memon, & Penrod, 2006](#)) that has led to guidelines for law enforcement personnel ([U.S. Department of Justice, 1999](#)). There have also been a number of applications of basic information processing to the design evaluations of various computer-based devices, such as modern flight management systems on aircraft ([John, Patton, Gray, & Morrison, 2012](#)). And there have been a number of applications to education, including reading instruction ([Rayner, Foorman, Perfetti, Pesetsky, & Seidenberg, 2002](#); [Seidenberg, 2013](#)) and computer-based systems for teaching mathematics ([Koedinger & Corbett, 2006](#)). Cognitive psychology is also making important contributions to our understanding of brain disorders that reflect abnormal

functioning, such as schizophrenia ([Cohen & Servan-Schreiber, 1992](#)) or autism ([Dinstein et al., 2012](#); [Just, Keller, & Kana, 2013](#)).

At many points in this book, Implications boxes will reinforce the connections between research in cognitive psychology and our daily lives (see, for example, [Implications 1.1](#)).

Implications 1.1

What Does Cognitive Psychology Tell Us about How to Study Effectively?

Cognitive psychology has identified methods that enable humans to read and remember a textbook like this one. This research will be described in [Chapters 6](#) and [13](#). The key idea is that it is crucial to identify the main points of each section of a text and to understand how these main points are organized. I have tried to help you do this by ending each section with a short summary sentence identifying its main point. I recommend that you use the following study technique to help you remember the material. This approach is a variant of the PQ4R (Preview, Question, Read, Reflect, Recite, Review) method discussed in [Chapter 6](#).

1. Preview the chapter. Read the section headings and summary statements to get a general sense of where the chapter is going and how much material will be devoted to each topic. Try to understand each summary statement, and ask yourself whether this is something you already know or believe.

Then, for each section of the book, go through the following steps:

2. Make up a study question by looking at the section heading and thinking of a related question that you will try to answer while you read the text. For instance, for the section “Intellectual Curiosity,” you might ask yourself, “What is there to be curious about in cognitive psychology?” This will give you an active goal to pursue while you read the section.
3. Read the section to understand it and answer your question. Try to relate what you are reading to situations in your own life. In the section “Intellectual Curiosity,” for example, you might try to think of scientific discoveries you have read about that seemed to require creativity.
4. At the end of each section, read the summary sentence and ask yourself whether that is the main point you got out of the section and why it is the main point. Sometimes you may need to go back and reread some parts of the section.



Hanquan Chen/Getty Images

Description

-

At the end of the chapter, engage in the following review process:

5. Go through the text, mentally reviewing the main points. Try to answer the questions you devised in step 2, plus any other questions that occur to you. Often, when preparing for an exam, it is a good idea to ask yourself what kind of exam questions you would make up for the chapter.

As we will learn in later chapters, such a study strategy improves one's memory of the text.

The results from the study of cognitive psychology have practical applications in other fields and in our daily lives.

The History of Cognitive Psychology

Cognitive psychology today is a vigorous science producing many interesting discoveries. However, this productive phase was a long time coming, and it is important to understand the history of the field that led to its current form.

Early History

In Western civilization, interest in human cognition can be traced to the ancient Greeks. Plato and Aristotle, in their discussions of the nature and origin of knowledge, speculated about memory and thought. These early philosophical discussions eventually developed into a centuries-long debate between two positions: [empiricism](#), which held that all knowledge comes from experience, and [nativism](#), which held that children come into the world with a great deal of innate knowledge. The debate intensified in the 17th, 18th, and 19th centuries, with such British philosophers as Berkeley, Locke, Hume, and Mill arguing for the empiricist view and such continental philosophers as Descartes and Kant propounding the nativist view. Although these arguments were philosophical at their core, they frequently slipped into psychological speculations about human cognition. (For further discussion of the empiricist–nativist debate, see [Chapter 14](#).)

During this long period of philosophical debate, sciences such as astronomy, physics, chemistry, and biology developed markedly. Curiously, however, it was not until the end of the 19th century that the scientific method was applied to the understanding of human cognition. Certainly, there were no technical or conceptual barriers to the scientific study of cognitive psychology earlier. In fact, many cognitive psychology experiments could have been performed and understood in the time of the ancient Greeks. But cognitive psychology, like many other sciences, suffered because of our egocentric, mystical, and confused attitudes about ourselves and our own nature, which made it seem inconceivable that the workings of the human mind could be subjected to scientific analysis. As a consequence, cognitive psychology as a science is less than 150 years old, and much of the first 100 years was spent freeing ourselves of the misconceptions that can arise when people engage in such an introverted enterprise as a scientific study of human cognition. It is a case of the mind studying itself.

Only in the last 150 years has it been realized that human cognition could be the subject of scientific study rather than philosophical speculation.

Psychology in Germany: Focus on Introspective Observation

The date usually cited as the beginning of psychology as a science is 1879, when Wilhelm Wundt established the first psychology

laboratory in Leipzig, Germany. Wundt's psychology was cognitive psychology (in contrast to other major divisions, such as comparative, clinical, or social psychology), although he had far-ranging views on many subjects. Wundt, his students, and many other early psychologists used a method of inquiry called [introspection](#), in which highly trained observers reported the contents of their own consciousness under carefully controlled conditions. The basic assumption was that the workings of the mind should be open to self-observation. Drawing on the empiricism of the British philosophers, Wundt and others believed that very intense self-inspection would be able to identify the primitive experiences out of which thought arose. Thus, to develop a theory of cognition, a psychologist had only to explain the contents of introspective reports.

Let us consider a sample introspective experiment. [Mayer and Orth \(1901\)](#) had their participants perform a free-association task. The experimenters spoke a word to the participants and then measured the amount of time the participants took to generate responses to the word. Participants then reported all their conscious experiences from the moment of stimulus presentation until the moment of their response. To get a feeling for this method, try to come up with an association for each of the following words:

coat	book
dot	bowl

After each association, think about the contents of your consciousness during the period between reading the word and

making your association.

In this experiment, many participants reported rather indescribable conscious experiences, not always seeming to involve sensations, images, or other concrete perceptions. This result started a debate over the issue of whether conscious experience could really be devoid of concrete content. As we will see in [Chapters 4](#) and [5](#), modern cognitive psychology has made real progress on this issue, but not by using introspection.

At the turn of the 20th century, German psychologists used a method of inquiry called introspection to study the workings of the mind.

Psychology in America: Focus on Behavior

Wundt's introspective psychology was not well accepted in America. Early American psychologists engaged in what they called "introspection," but it was not the intense analysis of the contents of the mind practiced by the Germans. Rather, it was largely an armchair avocation in which self-inspection was casual and reflective rather than intense and analytic. [William James's *Principles of Psychology* \(1890\)](#) reflects the best of this tradition, and many of the proposals in this work are still relevant today. The mood of American psychology was determined by the philosophical doctrines of pragmatism and functionalism. Many psychologists of the time were

involved in education, and there was a demand for an “action oriented” psychology that was capable of practical application. The intellectual climate in America was not receptive to the psychology from Germany that focused on such questions as whether or not the contents of consciousness were sensory.

One of the important figures of early American scientific psychology was Edward Thorndike, who developed a theory of learning that was directly applicable to classrooms. Thorndike was interested in such basic problems as the effects of reward and punishment on the rate of learning. To him, conscious experience was just excess baggage that could be largely ignored. Many of his experiments were done on animals, research that involved fewer ethical constraints than research on humans. Thorndike was probably just as happy that such participants could not introspect.

While introspection was being ignored at the turn of the century in America, it was getting into trouble on the continent. Various laboratories were reporting different types of introspections — each type matching the theory of the particular laboratory from which it emanated. It was becoming clear that introspection did not give one a clear window into the workings of the mind. Much that was important in cognitive functioning was not open to conscious experience. These two factors — the “irrelevance” of the introspective method and its apparent contradictions — laid the groundwork for the great behaviorist revolution in American psychology that occurred around 1920. John Watson and other

behaviorists led a fierce attack not only on introspectionism but also on any attempt to develop a theory of mental operations.

Behaviorism held that psychology was to be entirely concerned with external behavior and was not to try to analyze the workings of the mind that underlay this behavior:

Behaviorism claims that consciousness is neither a definite nor a usable concept. The Behaviorist, who has been trained always as an experimentalist, holds further that belief in the existence of consciousness goes back to the ancient days of superstition and magic. ([Watson, 1930, p. 2](#))

The Behaviorist began his own formulation of the problem of psychology by sweeping aside all medieval conceptions. He dropped from his scientific vocabulary all subjective terms such as sensation, perception, image, desire, purpose, and even thinking and emotion as they were subjectively defined. ([Watson, 1930, pp. 5–6](#))

The behaviorist program and the issues it spawned pushed research on cognition into the background of American psychology. The rat supplanted the human as the principal laboratory subject, and psychology turned to finding out what could be learned by studying animal learning and motivation. Quite a bit was discovered, but little was of direct relevance to cognitive psychology. Perhaps the most important lasting contribution of behaviorism is a set of sophisticated and rigorous techniques and principles for experimental study in all fields of psychology, including cognitive psychology.

Behaviorism was not as dominant in Europe. Psychologists such as Frederick Bartlett in England, Alexander Luria in the Soviet Union, and Jean Piaget in Switzerland were pursuing ideas that are still important in modern cognitive psychology. Cognitive psychology was an active research topic in Germany, but much of it was lost in the Nazi turmoil. A number of German psychologists immigrated to America and brought [Gestalt psychology](#) with them. Gestalt psychology claimed that the activity of the brain and the mind was more than the sum of its parts. This conflicted with the introspectionist program in Germany that tried to analyze conscious thought into its parts. In America, Gestalt psychologists found themselves in conflict with behaviorism for being concerned with mental structure at all. In America, Gestalt psychologists received the most attention for their claims about animal learning, and they were the standard targets for the behaviorist critiques, although some Gestalt psychologists became quite prominent in the field. For example, the Gestalt psychologist Wolfgang Kohler was elected to the presidency of the American Psychological Association. Although not a Gestalt psychologist, Edward Tolman was an American psychologist who did his research on animal learning and anticipated many ideas of modern cognitive psychology. Tolman's ideas were also frequently the target for criticism by the dominant behaviorist psychologists, although his work was harder to dismiss because he spoke the language of behaviorism.

In retrospect, it is hard to understand how American behaviorists could have taken such an anti-mental stand and clung to it for so

long. The unreliability of introspection did not mean that a theory of internal mental structure and process could not be developed, only that other methods were required (consider the analogy with physics, for example, where a theory of atomic structure was developed, although that structure could only be inferred, not directly observed). A theory of internal structure makes understanding human beings much easier, and the successes of modern cognitive psychology show that understanding mental structures and processes is critical to understanding human cognition.

In both the introspectionist and behaviorist programs, we see the human mind struggling with the effort to understand itself. The introspectionists held a naïve belief in the power of self-observation. The behaviorists were so afraid of falling prey to subjective fallacies that they refused to let themselves think about mental processes. Current cognitive psychologists seem to be much more at ease with their subject matter. They have a relatively detached attitude toward human cognition and approach it much as they would any other complex system.

Behaviorism, which dominated American psychology in the first half of the 20th century, rejected the analysis of the workings of the mind to explain behavior.

The Cognitive Revolution: AI, Information Theory, and

Linguistics

Cognitive psychology as we know it today took form in the two decades between 1950 and 1970, in the cognitive revolution that overthrew behaviorism. Three main influences account for its modern development. The first was research on human performance, which was given a great boost during World War II when governments badly needed practical information about how to train soldiers to use sophisticated equipment and how to deal with problems such as the breakdown of attention under stress. Behaviorism offered no help with such practical issues. Although the work during the war had a very practical bent, the issues it raised stayed with psychologists when they went back to their academic laboratories after the war. The work of the British psychologist Donald Broadbent at the Applied Psychology Research Unit in Cambridge was probably the most influential in integrating ideas from human performance research with new ideas that were developing in an area called *information theory*. Information theory is an abstract way of analyzing the processing of information. Broadbent and other psychologists, such as George Miller, Fred Attneave, and Wendell Garner, initially developed these ideas with respect to perception and attention, but such analyses soon pervaded all of cognitive psychology.

The second influence, which was closely related to the development of the information-processing approach, was a series of developments in computer science, particularly AI, which tries to get

computers to behave intelligently. Allen Newell and Herbert Simon, both at Carnegie Mellon University, spent most of their lives educating cognitive psychologists about the implications of AI (and educating workers in AI about the implications of cognitive psychology). Although the direct influence of AI-based theories on cognitive psychology has always been minimal, its indirect influence has been enormous. A host of concepts have been taken from computer science and used in psychological theories. Probably more important, observing how we can analyze the intelligent behavior of a machine has largely liberated us from our inhibitions and misconceptions about analyzing our own intelligence.

The third influence on cognitive psychology was [linguistics](#), the study of language (including the history, structure, acquisition, and use of language). In the 1950s Noam Chomsky, a linguist at the Massachusetts Institute of Technology, began to develop a new mode of analyzing the structure of language. His work showed that language was much more complex than had previously been believed and that many of the prevailing behaviorist formulations were incapable of explaining these complexities. Chomsky's linguistic analyses proved critical in enabling cognitive psychologists to fight off the prevailing behaviorist conceptions. George Miller, at Harvard University in the 1950s and early 1960s, was instrumental in bringing these linguistic analyses to the attention of psychologists and in identifying new ways of studying the psychology of language.

Cognitive psychology has grown rapidly since the 1950s. A milestone was the publication of Ulric Neisser's *Cognitive Psychology* in 1967, which gave a new legitimacy to the field. The book consisted of 6 chapters on perception and attention and 4 chapters on language, memory, and thought. Neisser's chapter division contrasts sharply with this book's, which has only 2 chapters on perception and attention and 10 on language, memory, and thought. My chapter division reflects a growing emphasis on higher mental processes. Following Neisser's work, another important event was the launch of the journal *Cognitive Psychology* in 1970. This journal has done much to define the field.

In the 1970s, a related new field called [cognitive science](#) emerged; it attempts to integrate research efforts from psychology, philosophy, linguistics, neuroscience, and AI. This field can be dated from the appearance of the journal *Cognitive Science* in 1976, which is the main publication of the Cognitive Science Society. The fields of cognitive psychology and cognitive science overlap. Speaking generally, cognitive science makes greater use of such methods as logical analysis and the computer simulation of cognitive processes, whereas cognitive psychology relies heavily on experimental techniques for studying behavior that grew out of the behaviorist era. This book draws on all methods but makes most use of cognitive psychology's experimental methodology.

During the 1950s–1970s, cognitive psychology broke away from behaviorism in response to developments in information theory, AI, and linguistics.

Information-Processing Analyses

The factors described in the previous sections of this chapter have converged in the [information-processing approach](#) to studying human cognition, and this has become the dominant approach in cognitive psychology. The information-processing approach attempts to analyze cognition as a set of steps for processing an abstract entity called “information.” Probably the best way to explain this approach is to describe a classic example of it. (See [Implications 1.2](#) for a general discussion of the credibility of research results in psychology and other fields.)

Implications 1.2

The Replicability Crisis

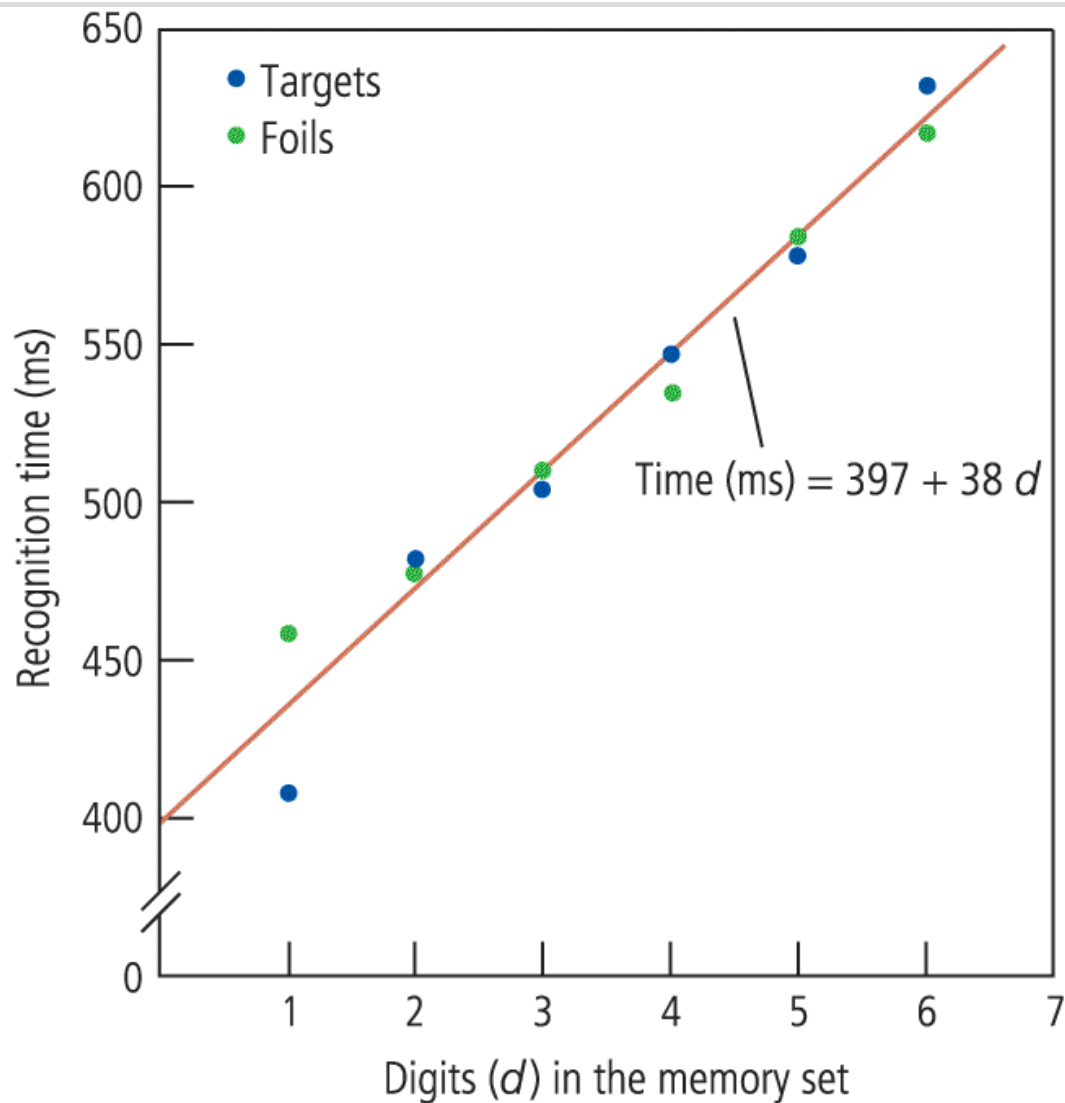
This book will largely report results and conclusions based on experiments that look for effects that are different across conditions. For instance, [Figure 1.1](#) shows increased response times in conditions where subjects have a larger set of items to remember. However, this is a result averaged from multiple trials and many subjects. Comparison of a particular pair of trials might show the reverse of the average trend — that is, a trial with a smaller set size might have a longer response time. There are many reasons for trial-to-trial variability, such as drift of attention and noise in the perceptual system. Psychology has developed statistical standards for determining if apparent effects in average data from an experiment are likely to be found reliably if the experiment were repeated. It is common to estimate what is called a [p-value](#), the probability that the result would be obtained by chance. A typical

threshold for believing an effect is that it have a p-value of less than .05. This would mean that there is a 95% chance that the effect is real.

However, psychology and other fields (including economics and medicine) are suffering what has been called a [replicability crisis](#), meaning that experimental results reported with p-values below .05 are not replicated when the experiments are repeated. One study examined 42 cognitive psychology experiments and found that only half (21) replicated ([Open Science, 2015](#)). There are many reasons why the results of a study might not be replicated. It is often impossible to reproduce the exact conditions of the original experiment and the same population of participants. There is also a bias in which papers get published. Experiments that fail to find effects are often considered not important enough to be published. Also, journals like to publish papers with surprising, and therefore newsworthy, results, and this often pushes the journals to accept papers that they might otherwise reject. This point is supported by a study that found that researchers could predict which papers in the prestigious journals *Science* and *Nature* reported results that would not replicate ([Camerer et al., 2018](#)). The nonreplicating results in those papers violated the researchers' sense of what was likely to be found, but often the results were newsworthy because they had great social potential — for instance, that reading literary fiction makes one more sensitive to other people's perspective.

Fortunately, much of what is reported in this textbook — like the effect of set size in [Figure 1.1](#) — has been replicated many times and seems firmly established. However, even if replicable, such well-established effects can be nuanced. For instance, while there is little question that response time increases with set size, there has been much controversy about whether it is a linear effect as Sternberg claimed and whether it is a result of the comparison process Sternberg described. In many places in this text we will describe alternative perspectives on established effects. We will also note the cases where there is some question about whether important effects can be replicated.

In a very influential paper published in 1966, Saul Sternberg described an experimental task and proposed a theoretical account of what people were doing in that task. In what has come to be called the [Sternberg paradigm](#), participants were shown a memory set consisting of a small number of digits, such as “3 9 7.” Then they were shown a probe digit and asked whether it was in the memory set, and they had to answer as quickly as possible. For example, 9 would be a positive probe for the “3 9 7” set; 6 would be a negative probe. Sternberg varied the number of digits in the memory set from 1 to 6 and measured how quickly participants could make this judgment. [Figure 1.1](#) shows his results as a function of the size of the memory set. Data are plotted separately for positive probes, or targets, and for negative probes, or foils. Participants could make these judgments quite quickly; latencies varied from about 400 to 600 milliseconds (ms) — a millisecond is a thousandth of a second. Sternberg found a nearly linear relationship between judgment time and the size of the memory set. As shown in [Figure 1.1](#), each one-digit increase in the size of the memory set resulted in an increase of about 38 ms in recognition time.



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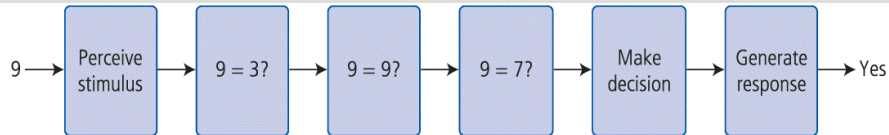
Data from Sternberg, 1969.

Figure 1.1 The Sternberg Paradigm: Recognition Time as a Function of Memory Set Size. The time needed to recognize a probe digit as a target (i.e., in the memory set) or as a foil (i.e., not in the memory set) increases with the number of items in the memory set. The straight line represents the linear function that fits the data best.

Description

The digits (d) in the memory set range from 0 to 7 in increments of 1. Recognition time ranges from 0 to 650; of which 400 to 650 are plotted in increments of 50. The line of best fit is upward sloping, it starts from the point (0, 400) and ends at the point (6.7, 645). An equation corresponding to the line reads, time (milliseconds) equals 397 plus 38 times d . The approximate points in the graph are as follows: (1, 410); (2, 470); (3, 500); (4, 540); (5, 575); (6, 630). The approximate points for foils are as follows: (1, 460); (2, 475); (3, 505); (4, 525); (5, 580); (6, 620).

Sternberg's account of how participants made these judgments was very influential; it exemplified what an abstract information-processing theory is like. As illustrated in [Figure 1.2](#), Sternberg assumed that when participants saw a probe stimulus such as a 9, they went through a series of information-processing stages. First the stimulus was encoded (i.e., perceived). Then the stimulus was compared to each digit in the memory set. To account for the slope of the line in [Figure 1.1](#), Sternberg assumed that it took 38 ms to complete each one of these comparisons. Then the participant had to decide on a response and finally generate it. Sternberg showed that different variables would influence each of these information-processing stages. Thus, if he degraded the stimulus quality by making the probe harder to read, participants took longer to make their judgments. This did not affect the slope of the [Figure 1.1](#) line, however, because it involved only the stage of stimulus perception in [Figure 1.2](#). Similarly, if he biased participants to say yes or no, the decision-making stage, but not other stages, was affected.



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Figure 1.2 The Sternberg Paradigm: Information-Processing Stages. Sternberg's analysis of the sequence of information-processing stages in his task.

Description

The flow diagram is as follows: 9 leads to perceive stimulus leads to 9 equals 3 question mark leads to 9 equals 9 question mark leads to 9 equals 7 question mark leads to make decision leads to generate response leads to yes.

It is worth noting the ways in which Sternberg's theory exemplifies a classic abstract information-processing account:

1. Information processing is discussed without any reference to the brain.
2. The processing of the information has a highly symbolic character. For example, his theory describes the human system as comparing the symbol 9 against the symbol 3, without considering how these symbols might be represented in the brain.
3. The processing of information can be compared to the way computers process information. In fact, Sternberg used the computer metaphor to explain why the comparison did not stop with the "9 = 9?" comparison in [Figure 1.2](#). He noted that this sort of exhaustive comparison process was used by computers of that time.

4. The measurement of time to make a judgment is a critical variable, because the information processing is conceived to be taking place in discrete stages. Flowcharts such as the one in [Figure 1.2](#) have been a very popular means of expressing the steps of information processing.

Each of these four features reflects a kind of narrowness in the classic information-processing approach to human cognition. Cognitive psychologists have gradually broadened their approach as they have begun to deal with more complex phenomena and as they have begun to pay more attention to the nature of information processing in the brain. For instance, this textbook has evolved over its editions to reflect this shift.

Information-processing analysis breaks a cognitive task down into a set of abstract information-processing steps.

Cognitive Neuroscience

Over the centuries there has been a lot of debate about the possible relationship between the mind and the body. Many philosophers, such as René Descartes, have advocated a position called [dualism](#), which posits that the mind and the body are separate kinds of entities. Although very few scientific psychologists believe in dualism, until recently many believed that brain activity was too obscure to provide a basis for understanding human cognition. Most of the research in cognitive psychology had relied on behavioral

methods, and most of the theorizing was of the abstract information-processing sort. However, with the steady development of knowledge about the brain and methods for studying brain activity, barriers to understanding the mind by studying the brain are slowly being eliminated, and brain processes are now being considered in almost all analyses of human cognition. The field of cognitive neuroscience is devoted to the study of how cognition is realized in the brain (i.e., the neural basis of cognition), with exciting new findings even in the study of the most complex thought processes. The remainder of this chapter will be devoted to describing some of the neuroscience knowledge and methods that now inform the study of human cognition, enabling us to see with growing precision how cognition unfolds in the brain (for example, at the end of this chapter I will describe a study of the neural processes that are involved as one solves a mathematical equation).

Cognitive neuroscience is developing methods that enable us to understand more and more about the neural basis of cognition.

Information Processing: The Communicative Neurons

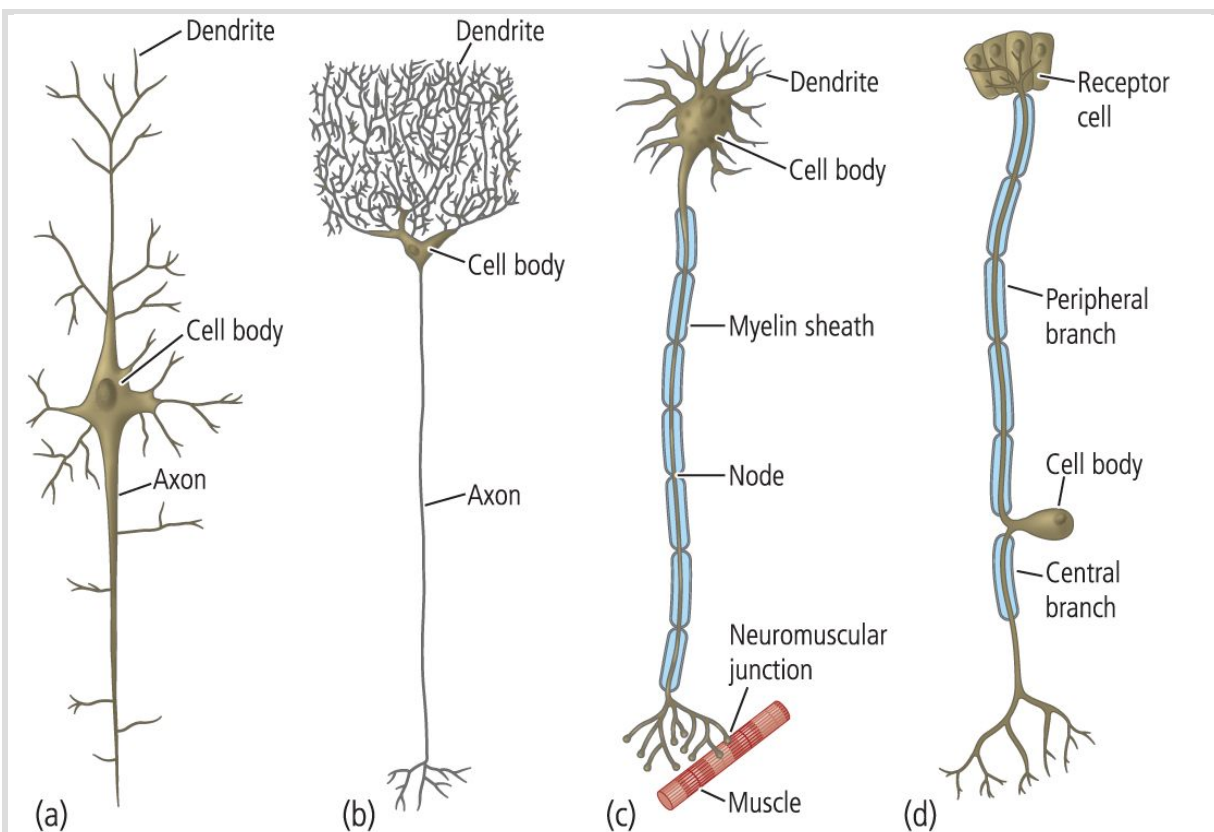
The brain is just one part of the nervous system, which also includes the various sensory systems that gather information from other parts of the body and the motor systems that control movement. In some cases, considerable information processing takes place via neurons outside the brain. From an information-processing point of view, neurons are the most important components of the nervous system.²

A [neuron](#) is a cell that receives and transmits signals through electrochemical activity. The human brain contains approximately 100 billion neurons, each of which may have roughly the processing capability of a computer. A considerable fraction of these 100 billion neurons are active simultaneously and do much of their information processing through interactions with one another. Imagine the information-processing power in 100 billion interacting computers! However, there are many tasks, such as finding square roots, at which a simple calculator can outperform all 100 billion neurons. Comprehending the strengths and weaknesses of the human nervous system is a major goal in understanding the nature of human cognition.

The Neuron

Neurons come in a wide variety of shapes and sizes, depending on their exact location and function. ([Figure 1.3](#) illustrates some of this variety.) There is, however, a generally accepted notion of what the

prototypical neuron is like, and individual neurons match up with this prototype to greater or lesser degrees. This prototype is illustrated in [Figure 1.4](#). The main body of the neuron is called the *soma* (or *cell body*). Typically, the soma is 5 to 100 micrometers (μm) in diameter. Attached to the soma are short branches called [dendrites](#), and extending from the soma is a long tube called the [axon](#). Axons can vary in length from a few millimeters to a meter.



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Figure 1.3 Some of the Variety of Neurons. (a) pyramidal cell; (b) cerebellar Purkinje cell; (c) motor neuron; (d) sensory neuron.

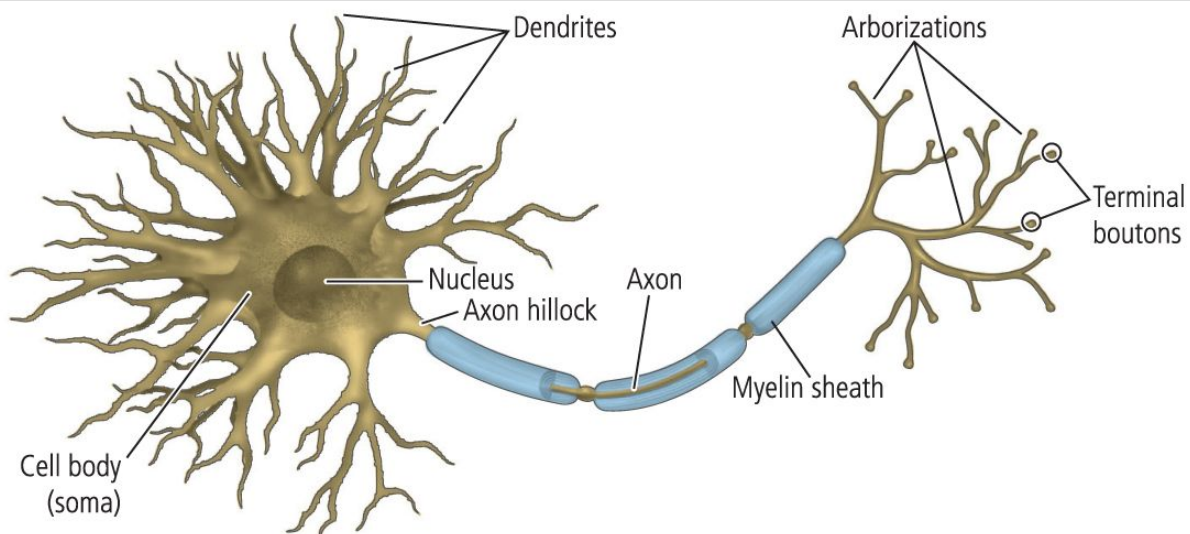
Description

Pyramidal cell: The center portion of the cell with an ovoid structure is labeled cell body. The branched extension from the cell body is labeled dendrite. A long, thin projection from the cell body is labeled axon.

Cerebellar Purkinje cell: The portion of cell with an ovoid structure is labeled cell body. A long, slender projection below the cell body is labeled axon. A complex branched extension above the cell body is labeled dendrite.

Motor neuron: The portion of cell with an ovoid structure is labeled cell body. The branched extensions from the cell body is labeled dendrite. The layer that insulates the axon is labeled myelin sheath. The gaps in the myelin sheath are labeled node. A cylindrical tube like structure at the bottom is labeled muscle. The contact point between the axon terminal and the muscle is labeled neuromuscular junction.

Sensory neuron: The center portion of the cell with an ovoid structure is labeled cell body. A receptor cell is at the top and branched protrusions are at the bottom. The peripheral branch is on the upper side of the cell body between the cell body and the receptor cell. The central branch is below the cell body.



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Figure 1.4 A Schematic Representation of a Typical Neuron.

Description

The structure shows a rounded cell body with an ovoid structure at the center labeled nucleus. The branches extending from the cell body are labeled dendrites. A long, thin projection from the cell body is labeled axon. The part that connects the cell body and the axon is labeled axon hillock. The axon is shielded within a layer labeled as the myelin sheath. A fine branching structure at the end of the axon is labeled Arborizations. The Arborizations have terminal buttons at their ends.

Axons provide the fixed paths by which neurons communicate with one another. The axon of one neuron extends toward the dendrites of other neurons. At its end, the axon branches into a large number of arborizations. Each arborization ends in terminal boutons, each of which almost makes contact with a dendrite of another neuron. The gap separating the terminal bouton and the dendrite is typically in the range of 10 to 50 nanometers (nm). This near contact between axon and dendrite is called a [synapse](#). Typically, neurons communicate by releasing chemicals, called [neurotransmitters](#), from the terminal bouton on one side of the synapse; these chemicals act on the membrane of the receptor dendrite to change its polarization, or electric potential. The inside of the membrane covering the entire neuron tends to be 70 millivolts (mV) more negative than the outside, due to the greater concentration of negative chemical ions inside and positive ions outside. The existence of a greater concentration of positive sodium ions on the outside of the membrane is particularly important to the functioning of the neuron. Depending on the nature of the neurotransmitter, the potential difference can decrease or

increase. Synapses that release neurotransmitters that decrease the potential difference are called [excitatory synapses](#), and those that increase the difference are called [inhibitory synapses](#).

On average, the dendrites of a typical neuron form about 1,000 synapses with other neurons, and the terminal boutons of a typical neuron form synapses with about 1,000 other neurons. The change in electric potential due to any one synapse is rather small, but the individual excitatory and inhibitory effects will accumulate. If there is enough net excitatory input, the potential difference in the soma of the receiving neuron can drop sharply, and if the reduction in potential is large enough, a depolarization will occur at the axon hillock, where the axon joins the soma (see [Figure 1.4](#)). This depolarization is caused by a rush of positive sodium ions into the inside of the neuron. The inside of the neuron momentarily (for a millisecond) becomes more positive than the outside. This sudden change, called an [action potential](#) (or spike), will propagate down the axon. That is, the potential difference will suddenly and momentarily change down the axon. The rate at which this change travels can vary from 0.5 to 130 m/s, depending on the characteristics of the axon — such as the degree to which the axon is covered by a myelin sheath (the more myelination, the faster the transmission). When the nerve impulse (i.e., the action potential) reaches the end of the axon, it causes neurotransmitters to be released from the terminal boutons, thus continuing the cycle.

To review: Changes in electric potential accumulate on a cell body, reach a threshold, and cause an action potential to propagate down an axon. This pulse in turn causes neurotransmitters to be sent from the axon's terminal boutons to the dendrites of other neurons, causing changes in those neurons' membrane potential. This sequence is the core of neural information processing, yet intelligence arises from this simple system of interactions. The challenge for cognitive neuroscience is to understand how.

The time required for this neural communication to complete the path from one neuron to another is roughly 10 ms — definitely more than 1 ms and definitely less than 100 ms; the exact speed depends on the characteristics of the neurons involved. This is much slower than the billions of operations that a modern computer can perform in one second. However, there are billions of these activities occurring simultaneously throughout the brain.

Neurons communicate by releasing chemicals, called neurotransmitters, from an axon terminal on one side of a synapse that act on the membrane of a dendrite of the receiving neuron to change the electric potential across the membrane.

Neural Representation of Information

Two quantities are particularly important to the representation of information in the brain. First, as we just saw, the membrane

potential can be more or less negative. Second, the number of action potentials, or nerve impulses, an axon transmits per second, called its [rate of firing](#), can vary from very few to upward of 100. The greater the rate of firing, the greater the effect the axon will have on the cells with which it synapses. We can contrast information representation in the brain with information representation in a computer, where individual memory cells, or bits, can have just one of two values — off (0) or on (1). A typical computer cell does not have the continuous variation of a typical neural cell.

We can think of a neuron as having an activation level that corresponds roughly to the firing rate on the axon or to the degree of depolarization on the membrane of the receiving neuron. Neurons interact by driving up the activation level of other neurons (excitation) or by driving down their activation level (inhibition). All neural information processing takes place in terms of these excitatory and inhibitory effects; they are what underlies human cognition.

How do neurons represent information? Evidence suggests that individual neurons respond to specific features of a stimulus. For instance, some neurons are most active when there is a line in the visual field at a particular angle (as described in [Chapter 2](#)), while other neurons respond to more complex sets of features. For instance, there are neurons in the monkey brain that appear to be most responsive to faces ([Bruce, Desimone, & Gross, 1981](#); [Desimone, Albright, Gross, & Bruce, 1984](#); [Perrett, Rolls, & Caan, 1982](#)). It is not possible, however, that single neurons encode all the

concepts and shades of meaning we possess. Moreover, the firing of a single neuron cannot represent the complexity of structure in a face.

If a single neuron cannot represent the complexity of our cognition, how are complex concepts and experiences represented? How can the activity of neurons represent our concept of baseball; how can it result in our solution of an algebra problem; how can it result in our feeling of frustration? Similar questions can be asked of computer programs, which have been shown to be capable of answering questions about baseball, solving algebra problems, and displaying frustration. Where in the millions of off-and-on bits in a computer program does the concept of baseball lie? How does a change in a bit result in the solution of an algebra problem or in a feeling of frustration? However, these questions fail to see the forest for the trees. The concept of a sport, a problem solution, or an emotion occurs in large patterns of bit changes. Similarly, human cognition is achieved through large patterns of neural activity. For instance, in an early study using brain imaging (see the section “[Neural Imaging Techniques](#)” later in this chapter), [Mazoyer et al. \(1993\)](#) compared the brain activation of participants when they heard different kinds of speech. They found activity in more and more regions of the brain as participants went from hearing meaningless speech (i.e., speech in an unknown language) to hearing lists of words to hearing meaningful stories. This result indicates that our understanding of a meaningful story involves activity in many regions of the brain.

It is informative to think about how a computer stores information. Consider a simple case: the spelling of words. Most computers have codes by which individual patterns of binary values (1s and 0s) represent letters. [Table 1.1](#) illustrates the use of one coding scheme, called ASCII; the table shows a pattern of 0s and 1s that codes the words *COGNITIVE PSYCHOLOGY*.

**TABLE 1.1 ASCII Coding* of the Words
*COGNITIVE PSYCHOLOGY***

C	O	G	N	I	T	I	V	E	
1	1	0	0	1	1	1	0	1	
1	1	1	1	1	1	1	1	1	
0	0	0	0	0	0	0	0	0	
0	0	0	0	0	1	0	1	0	
0	1	0	1	1	0	1	0	0	
0	1	1	1	0	1	0	1	1	
1	1	1	1	0	0	0	1	0	
1	1	1	0	1	0	1	0	1	
P	S	Y	C	H	O	L	O	G	Y
0	0	0	1	0	1	1	1	0	0
1	1	1	1	1	1	1	1	1	1
0	0	0	0	0	0	0	0	0	0
1	1	1	0	0	0	0	0	0	1
0	0	1	0	1	1	1	1	0	1
0	0	0	0	0	1	1	1	1	0

0	1	0	1	0	1	0	1	1	0
0	1	1	1	0	1	0	1	1	1

*7-bit with even parity. The pattern of 0s and 1s below each letter is the code for that letter.

Similarly, the brain can represent information in terms of patterns of neural activity rather than simply as cells firing. The code in [Table 1.1](#) includes redundant bits that allow the computer to correct errors should certain bits be lost (note that each column has an even number of 1s, which reflects the added bits for redundancy). As in a computer, it seems that the brain codes information redundantly, so that even if certain cells are damaged, the brain can still determine what the pattern is encoding. It is generally thought that the brain uses schemes for encoding information and achieving redundancy that are very different from the ones a computer uses. It also seems that the brain uses a much more redundant code than a computer does because the behavior of individual neurons is not particularly reliable.

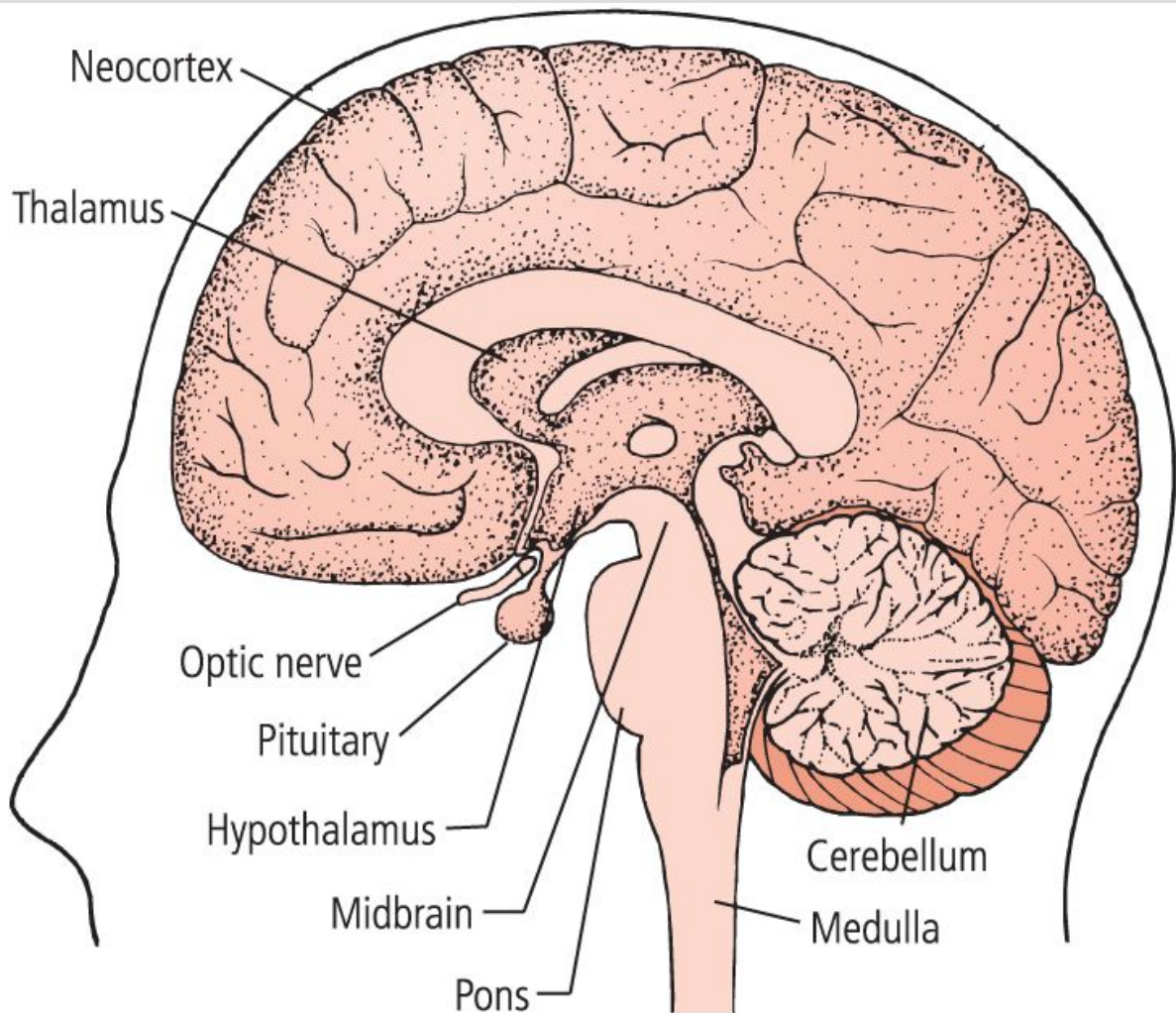
So far, we have talked only about patterns of neural activation. Such patterns, however, are transitory. The brain does not maintain the same pattern for minutes, let alone days. This means that neural activation patterns cannot encode our permanent knowledge about the world. It is thought that the memories that encode this knowledge are created by changes in the synaptic connections among neurons. By changing the synaptic connections, the brain can enable itself to reproduce specific patterns. Although there is not a great deal of

growth of new neurons or new synapses in the adult, the effectiveness of synapses can change in response to experience. There is evidence that synaptic connections do change during learning, with both increased release of neurotransmitters ([Kandel & Schwartz, 1984](#)) and increased sensitivity of dendritic receptors ([Lynch & Baudry, 1984](#)). We will discuss some of this research in [Chapter 6](#).

Information is represented by patterns of activity across many regions of the brain and by changes in the synaptic connections among neurons that allow these patterns to be reproduced.

Organization of the Brain

The central nervous system consists of the brain and the spinal cord. The major function of the spinal cord is to carry motor messages from the brain to the muscles, and sensory messages from the body to the brain. [Figure 1.5](#) shows a cross section of the brain with some of the more prominent neural structures labeled. The lower parts of the brain are evolutionarily more primitive. The higher portions are well developed only in the higher species.



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Figure 1.5 The Human Brain: Cross Section. A cross-sectional view of the brain showing some of its major components.

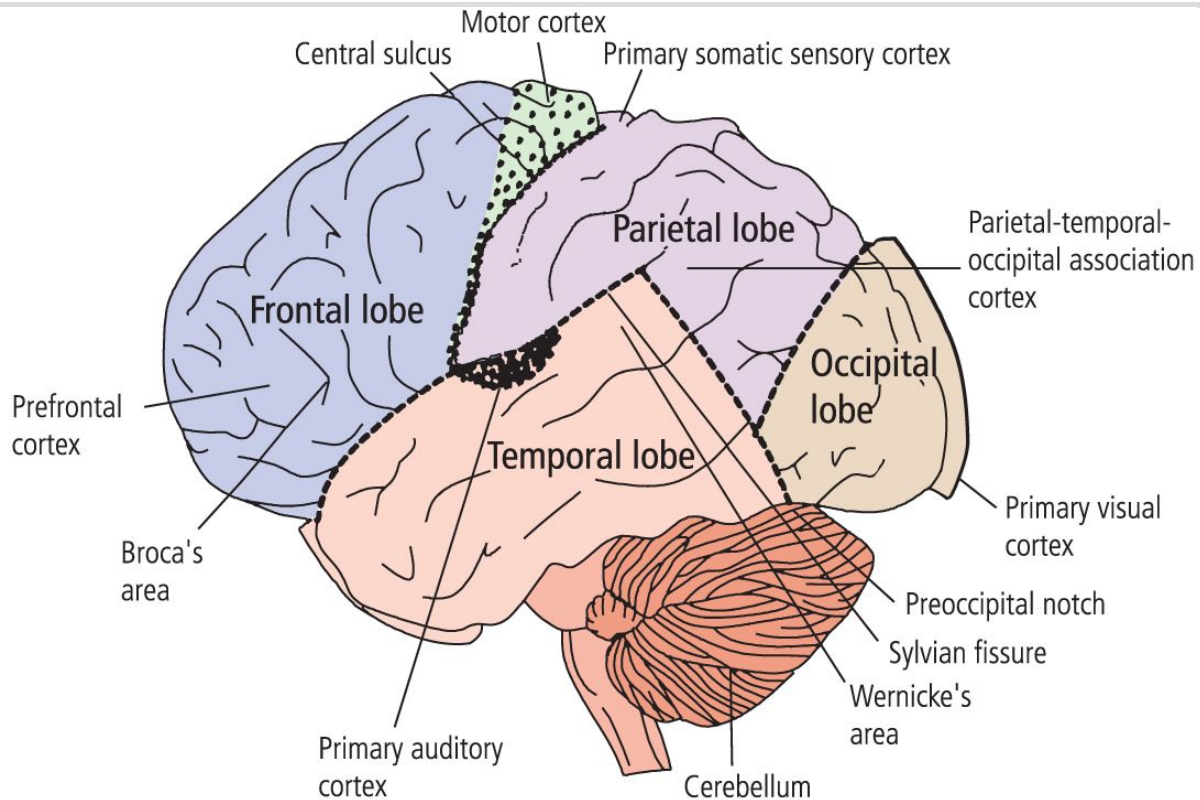
Description

The outermost layer of cerebrum is labeled Neocortex. A large mass of matter in the dorsal part of fore brain is labeled thalamus. The optic nerve is connected to the underside of the thalamus. A small structure with a thin stem attached to the brain underneath the optic nerve is labeled pituitary. A small region in the brain located above and to the right of the

pituitary is labeled hypothalamus. A portion below the hypothalamus in the brainstem is labeled midbrain. A curved protruding region below the mid brain in the brainstem is labeled pons. The stem like extension below the pons is labeled medulla. A tightly folded layer of white and gray matter located in the lower right side of the brain stem is labeled cerebellum.

Correspondingly, it appears that the lower portions of the brain are responsible for more basic functions. The medulla controls breathing, swallowing, digestion, and heartbeat. The hypothalamus regulates the expression of basic drives. The cerebellum plays an important role in motor coordination and voluntary movement. The thalamus serves as a relay station for motor and sensory information from lower areas to the neocortex. Although the cerebellum and thalamus serve these basic functions, they also have evolved to play an important role in higher human cognition, as we will discuss later.

The [neocortex](#) (the main part of the [cerebral cortex](#)³) is the most recently evolved portion of the brain. Although it is quite small and primitive in many mammals, it accounts for a large fraction of the human brain (see [Figure 1.6](#)). The human neocortex can be thought of as a rather thin neural sheet with a surface area of about 2,500 cm². To fit into the skull, it has to be highly convoluted, and the large amount of folding and wrinkling of the cortex is one of the striking physical differences between the human brain and the brains of lower mammals. A bulge of the cortex is called a [gyrus](#), and a crease passing between gyri is called a [sulcus](#) (plural *sulci*).



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Figure 1.6 The Human Brain: Side View. A side view of the cerebral cortex showing the four lobes — frontal, temporal, parietal, and occipital — of each hemisphere (blue-shaded areas) and other major components of the cerebral cortex.

Description

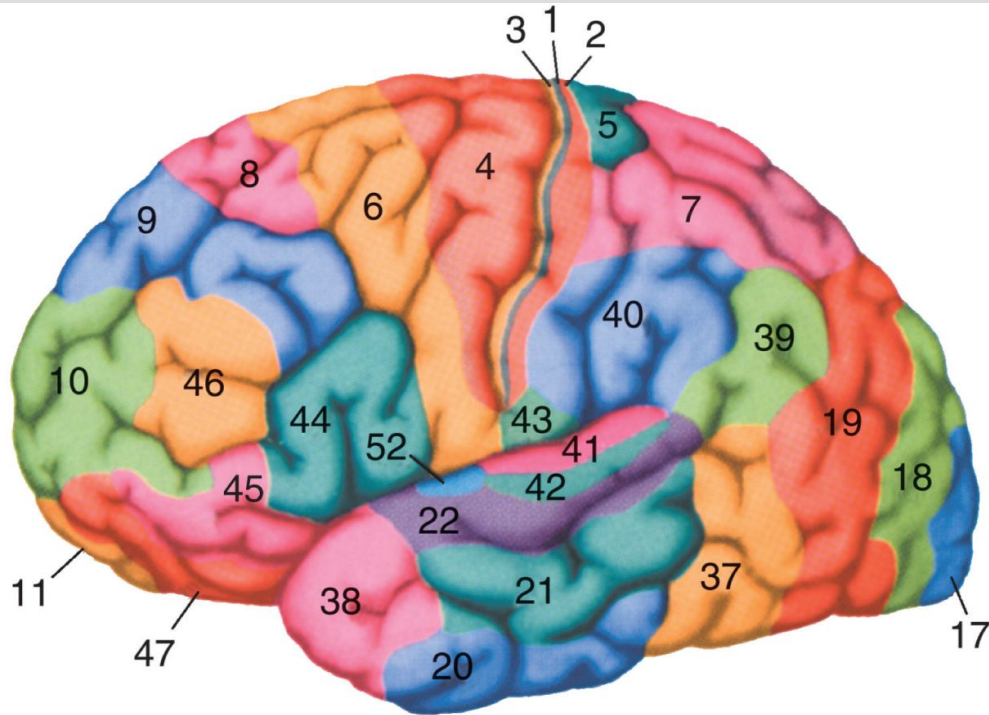
The four lobes are as follows: frontal lobe, parietal lobe, temporal lobe, and occipital lobe. The front portion of cerebral hemisphere which is positioned in front of parietal lobe and above temporal lobe is labeled frontal lobe. The cerebral cortex covering the front part of the frontal lobe is labeled prefrontal cortex. A region in the posterior section of left frontal lobe of the dormant hemisphere is labeled Broca's area. The region separating the parietal lobe from the frontal lobe is labeled central sulcus. A region of the frontal lobe anterior to the central sulcus is labeled motor cortex. A region located near the center of the brain, behind the frontal lobe is labeled parietal lobe. A region immediately behind the motor

cortex on the parietal lobe is labeled primary somatic sensory cortex. The association region of parietal-temporal-occipital in the cerebral cortex is labeled parietal-temporal-occipital association cortex. The posterior region of the cerebral cortex behind the parietal lobe is labeled occipital lobe. A region on the right outer surface of occipital lobe is labeled primary visual cortex. The region below the frontal lobe and parietal lobe is labeled temporal lobe. A region lying superior to the temporal gyrus of the temporal lobe is labeled primary auditory cortex. A posterior section of temporal gyrus in the left hemisphere on the temporal lobe is labeled Wernicke's area. A dashed line separating the frontal and parietal lobe from the temporal lobe is labeled Sylvian fissure. A tightly folded and crumpled part below the temporal lobe and behind the brain stem is labeled cerebellum. A small lateral border with a deep recess just before the occipital lobe is labeled preoccipital notch.

The neocortex is divided into left and right hemispheres. One of the interesting curiosities of anatomy is that the right part of the body tends to be connected to the left hemisphere and the left part of the body to the right hemisphere. Thus, the left hemisphere controls motor function and sensation in the right hand. The right ear is most strongly connected to the left hemisphere. The neural receptors in either eye that receive input from the left part of the visual world are connected to the right hemisphere (as [Chapter 2](#) will explain with respect to [Figures 2.4](#) and [2.5](#)).

[Brodmann \(1909/1960\)](#) identified 52 distinct regions of the human cortex (see [Figure 1.7](#)), based on differences in the cell types in various regions. Many of these regions proved to have functional differences as well. The cortical regions of each hemisphere are

typically organized into four lobes: frontal, parietal, occipital, and temporal, which are separated by major sulci (see [Figure 1.6](#)). The [occipital lobe](#) contains the primary visual areas. The [parietal lobe](#) handles some perceptual functions, including spatial processing and representation of the body. It is also involved in control of attention, as we will discuss in [Chapter 3](#). The [temporal lobe](#) receives input from the occipital lobe and is involved in object recognition. It also has the primary auditory areas and Wernicke's area, which is involved in language processing. The [frontal lobe](#) has two major functions: The back portion of the frontal lobe is involved primarily with motor functions. The front portion, called the [prefrontal cortex](#), is thought to control higher-level processes, such as planning. The frontal portion of the brain is disproportionately larger in primates than in most other mammals, and among primates, humans are distinguished by having disproportionately larger anterior portions of the prefrontal cortex (area 10 in [Figure 1.7](#)) ([Semendeferi, Armstrong, Schleicher, Zilles, & Van Hoesen, 2001](#)).



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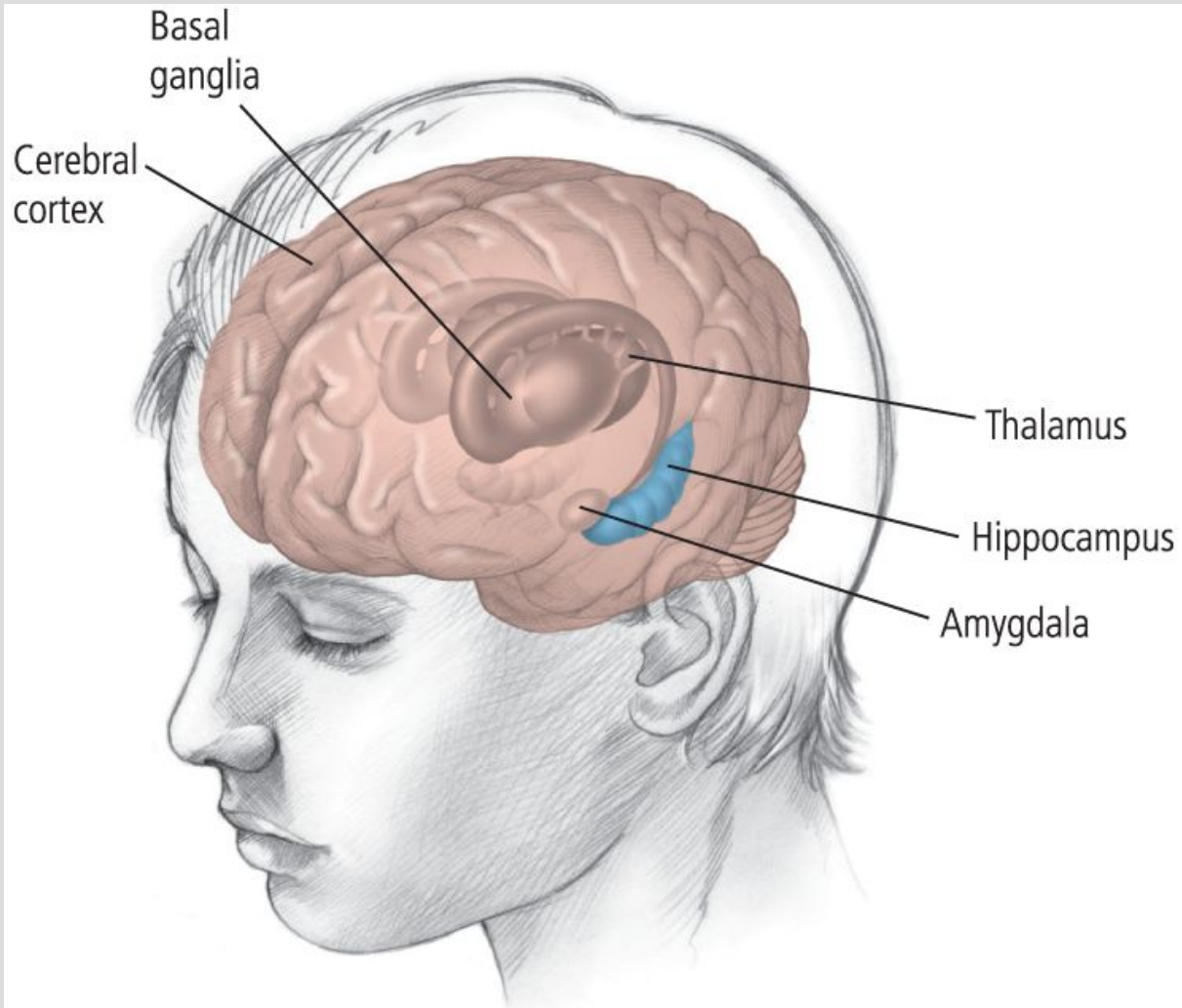
Figure 1.7 Some of the 52 Distinct Regions of the Cerebral Cortex Identified by Brodmann, Based on Cell Structure and Arrangement. Most of the numbered regions missing from this figure (areas 12–16, 23–36, and 48–51) are wrapped inside the brain and so are not visible in this exterior view.

Description

The Brodmann regions are labeled from 1 to 52 except the areas 12 to 16, 23 to 36, and 48 to 51. The regions are colored and numbered. The regions 1, 5, 21, 42, 43, and 44 are colored in dark green. The regions 2, 4, 19, 11 are colored in red. The regions 3, 6, 11, 37, and 46 are colored in yellow. The regions 9, 17, 20, 40, and 52 are colored in blue. The regions 10, 39, and 18 are colored in light green. The regions 7, 8, 38, 41, and 45 are colored in pink. The region 22 is colored in purple.

The neocortex is not the only region that plays a significant role in higher-level cognition. Many important circuits go from the cortex to

subcortical structures and back again. A particularly significant group of subcortical structures is the limbic system, which is at the border between the cortex and lower structures. Among the structures making up the limbic system are the [amygdala](#) and the [hippocampus](#) (both of which are located inside the temporal lobe in each hemisphere). As we will see in later discussions, the amygdala is involved in emotional responses. The hippocampus appears to be critical to human memory; damage to the hippocampus and to other nearby structures produces severe amnesia, as we will see in [Chapter 7. Figure 1.8](#) illustrates the amygdala and hippocampus, along with the thalamus, an important subcortical structure that is not part of the limbic system.



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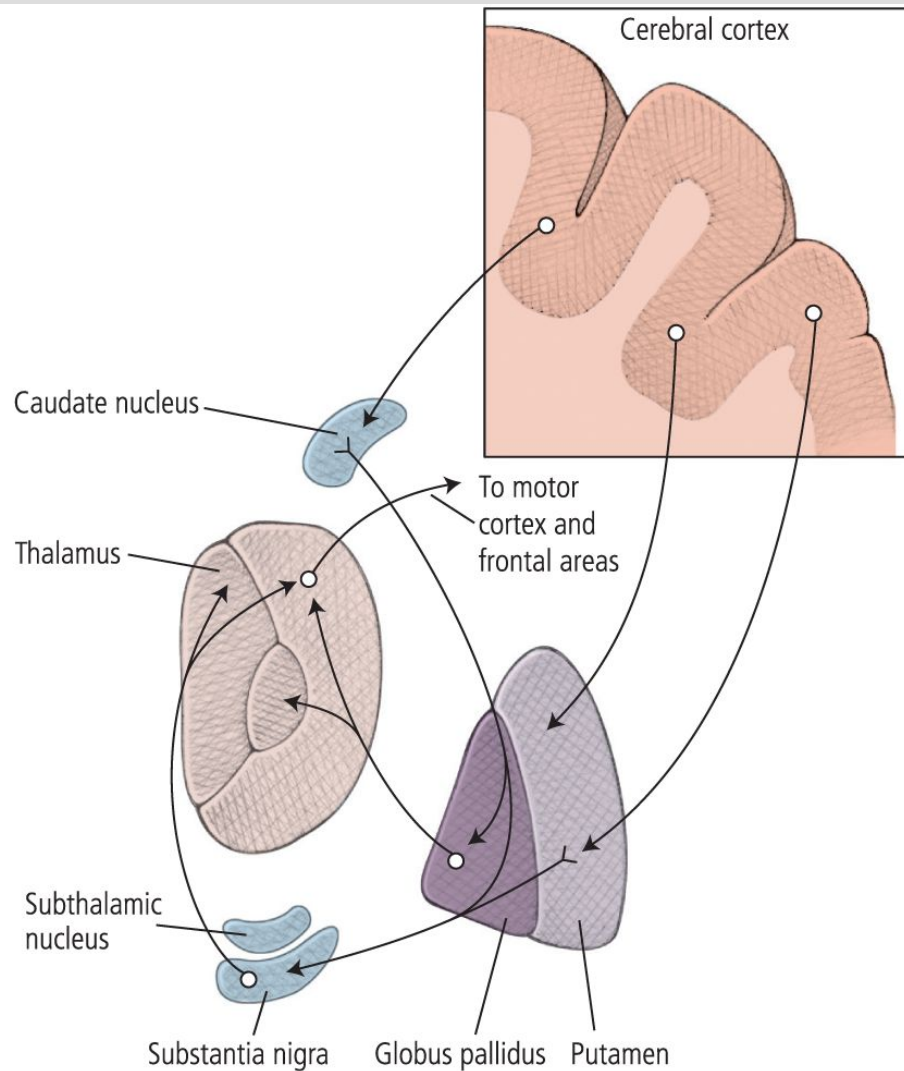
Figure 1.8 The Human Brain: Some Subcortical Structures. Structures under the cortex include those that make up the limbic system (the hippocampus, amygdala, and other structures), the thalamus, and the basal ganglia.

Description

The cerebral cortex constitutes the uppermost part of the brain. A backwards C-shaped structure at the center, encompassing an ovoid structure, is labeled basal ganglia. The thalamus is located in the midbrain, posterior to the ovoid structure. A small curved region in the

medial temporal lobe below the basal ganglia is labeled hippocampus, attached to the inferior of the basal ganglia. An almond-shaped structure at the inferior tip of the basal ganglia is labeled amygdala.

Another important collection of subcortical structures is the **basal ganglia**. The major structures and critical connections of the basal ganglia are illustrated in **Figure 1.9**. The basal ganglia are involved both in basic motor control and in the control of complex cognition. These structures receive signals from almost all areas of the cortex and send signals to the frontal cortex. Disorders such as Parkinson's disease and Huntington's disease result from damage to the basal ganglia. Although people suffering from these diseases have dramatic motor control deficits characterized by tremors and rigidity, they also have difficulties in cognitive tasks. The cerebellum — in addition to its major role in motor control, as noted above — also seems to play a role in higher-order cognition. Many cognitive deficits have been observed in patients with damage to the cerebellum.



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 Information from Gazzaniga, Ivry, & Mangun, 2002.

Figure 1.9 Basal Ganglia. The major structures of the basal ganglia (blue-shaded areas) include the caudate nucleus, the subthalamic nucleus, the substantia nigra, the globus pallidus, and the putamen. The critical connections (inputs and outputs) of the basal ganglia are illustrated with arrows.

Description

A magnified view of the cerebral cortex is shown, parts of the outer layer corresponding to different labeled parts. A bean shaped structure is labeled caudate nucleus. A large almost round shaped structure is

labeled putamen and a triangular shaped structure attached to the putamen is labeled globus pallidus, which contains the caudate nucleus. A medium bean shaped structure is labeled substantia nigra, which contains the globus pallidus, and a small bean shaped structure above substantia nigra is labeled subthalamic nucleus. A rounded structure with three sections is labeled thalamus and includes the subthalamic nucleus within the outer two sections, and the globus pallidus in the central and larger outer portion. One part of cerebral cortex connects with caudate nucleus which connects with globus pallidus and substantia nigra. Another part of cerebral cortex connects with putamen. Another part also connects with putamen. The larger outer portion of the thalamus connects to motor cortex and frontal areas.

The brain is organized into a number of distinct areas, which serve different types of functions, with the neocortex playing the major role in higher cognitive functions.

Localization of Function

The left and right hemispheres of the cerebral cortex appear to be somewhat specialized for different types of processing. In general, the left hemisphere seems to be associated with linguistic and analytic processing, whereas the right hemisphere is associated with perceptual and spatial processing. The left and right hemispheres are connected by a broad band of fibers called the corpus callosum. The corpus callosum has been surgically severed in some patients to prevent epileptic seizures. Such patients are referred to as split-brain patients. The operation is typically successful, and patients seem to function fairly well. Much of the

evidence for the differences between the hemispheres comes from research with these patients. In one experiment, the word *key* was flashed on the left side of a screen the patient was viewing. Because it was on the left side of the screen, it would be received by the right, nonlinguistic hemisphere. When asked what was presented on the screen, the patient was not able to say because the left hemisphere (where linguistic processing mainly occurs) did not know. However, the patient's left hand (but not the right) was able to pick out a key from a set of objects hidden from view.

The linguistic advantage for the left hemisphere has been shown in a variety of studies with split-brain patients. For instance, commands might be presented to these patients in the right ear (and hence to the left hemisphere) or in the left ear (and hence to the right hemisphere). The right hemisphere can comprehend only the simplest linguistic commands, whereas the left hemisphere displays full comprehension. However, when tasked with arranging blocks to match a pictorial design without instruction, the left hand (and right hemisphere) does better. The right hemisphere can better follow pictorial information, whereas the left can better follow verbal information ([Gazzaniga, 1967](#)).

Research with other patients who have had damage to specific brain regions indicates that there are areas in the left hemisphere, called [Broca's area](#) and [Wernicke's area](#) (see [Figure 1.6](#)), that seem critical for speech, because damage to them results in [aphasia](#), the severe impairment of speech. These may not be the only neural

areas involved in speech, but they certainly are important. Different language deficits appear depending on whether the damage is to Broca's area or Wernicke's area. People with Broca's aphasia (i.e., damage to Broca's area) speak in short, ungrammatical sentences. For instance, when one patient was asked whether he drives home on weekends, he replied:

Why, yes ... Thursday, er, er, er, no, er, Friday ... Bar-ba-ra ... wife ... and, oh, car ... drive ... purnpike ... you know ... rest and ... teevee. ([Gardner, 1975, p. 61](#))

In contrast, patients with Wernicke's aphasia speak in fairly grammatical sentences that are almost devoid of meaning. Such patients have difficulty with their vocabulary and generate "empty" speech. The following is the answer given by one such patient to the question "What brings you to the hospital?"

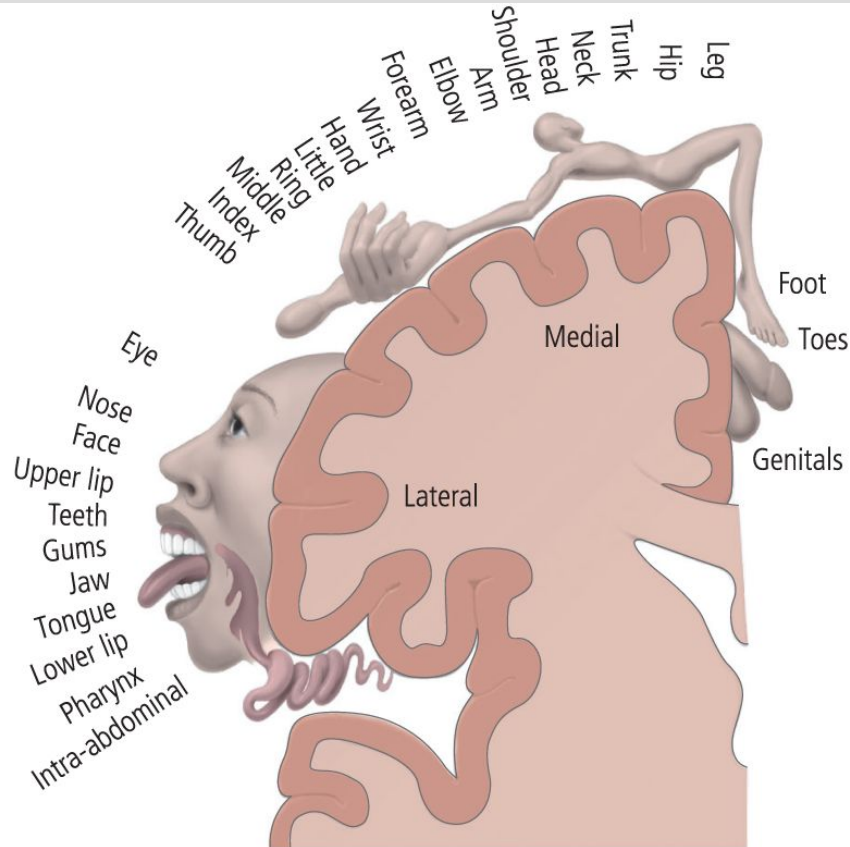
Boy, I'm sweating, I'm awful nervous, you know, once in a while I get caught up, I can't mention the tarripoi, a month ago, quite a little, I've done a lot well. I impose a lot, while, on the other hand, you know what I mean, I have to run around, look it over, trebbin and all that sort of stuff. ([Gardner, 1975, p. 68](#))

Different specific areas of the brain support different cognitive functions.

Topographic Organization

In many areas of the cortex, information processing is structured spatially in what is called a [topographic organization](#). For instance, in the visual area at the back of the cortex, adjacent areas represent

information from adjacent areas of the visual field (see the discussion around [Figure 2.5](#)). A similar principle of organization governs the representation of the body in the motor cortex and the somatosensory cortex along the central sulcus. Adjacent parts of the body are represented in adjacent parts of the neural tissue. [Figure 1.10](#) illustrates the representation of the body along the somatosensory cortex. Note that the relative size of body parts is distorted, showing that certain areas of the body receive considerably more neural representation than other areas. It turns out that the overrepresented areas correspond to those that are more sensitive. Thus, for instance, we can make more subtle discriminations among tactile stimuli on the hands and face than we can on the back or thigh. Similarly, in the visual cortex, there is an overrepresentation of the center of our visual field, where we have the greatest visual acuity (also shown in [Figure 2.5](#)).



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Figure 1.10 Topographic Organization of the Somatosensory Cortex. A cross section of the somatosensory cortex, showing how the human body is mapped in the neural tissue.

Description

The parts controlled by lateral region are as follows: Eye, nose, face, upper lip, teeth, gums, jaw, tongue, lower lip, pharynx, intra-abdominal. The parts controlled by the medial region are as follows: Thumb, index, middle, ring, little, hand, wrist, forearm, elbow, arm, shoulder, head, neck, trunk, hip, leg, foot, toes, and genitals.

It is thought that topographic maps facilitate the interactions of neurons processing similar regions ([Crick & Asanuma, 1986](#)).

Although there are fiber tracks that connect widely separated regions of the brain, the majority of the connections are among nearby neurons. This emphasis on local connections serves to minimize both the communication time between neurons and the amount of neural tissue that must be devoted to connecting them. The extreme of localization is seen in cortical minicolumns ([Buxhoeveden & Casanova, 2002](#)) — tiny vertical columns of about 100 neurons that have a very restricted mission. For instance, cortical minicolumns in the primary visual cortex are specialized to process information about one orientation of a line or an edge, from one location in the visual field, in one eye.

Neurons in a minicolumn do not represent a precise location with pinpoint accuracy but rather a range of nearby locations. This relates to another aspect of neural information processing called *coarse coding*, which refers to the fact that single neurons seem to respond to a range of events. For instance, when the neural activity from a single neuron in the somatosensory cortex is recorded, we can see that the neuron does not respond only when a single point of the body is stimulated, but rather when any point on a large patch of the body is stimulated. How, then, can we know exactly what point has been touched? That information is recorded quite accurately, but not in the response of any particular cell. Instead, different cells will respond to different overlapping regions of the body, and any point will evoke a different set of cells. Thus, the location of a point is reflected by the pattern of activation, which reinforces the idea that neural information tends to be represented in patterns of activation.

Adjacent cells in the cortex tend to process sensory stimuli from adjacent areas of the body, with the precise location of stimuli indicated by patterns of activation among cells.

Methods in Cognitive Neuroscience

How does one go about understanding the neural basis of cognition? Much of the past research in neuroscience has been done on animals, sometimes involving the surgical removal of various parts of the cortex. By observing the deficits these operations have produced, it is possible to infer the functions of the regions removed. Other research has recorded the electrical activity in particular neurons or regions of neurons. By observing what activates these neurons, one can infer what they do. However, there is considerable uncertainty about how much these animal results generalize to humans. The difference between the cognitive potential of humans and that of most other animals is enormous. With the possible exception of other primates, it is difficult to get other animals to engage in even the simplest kinds of cognitive processes that characterize humans. This has been the great barrier to understanding the neural basis of higher-level human cognition.

Neural Imaging Techniques

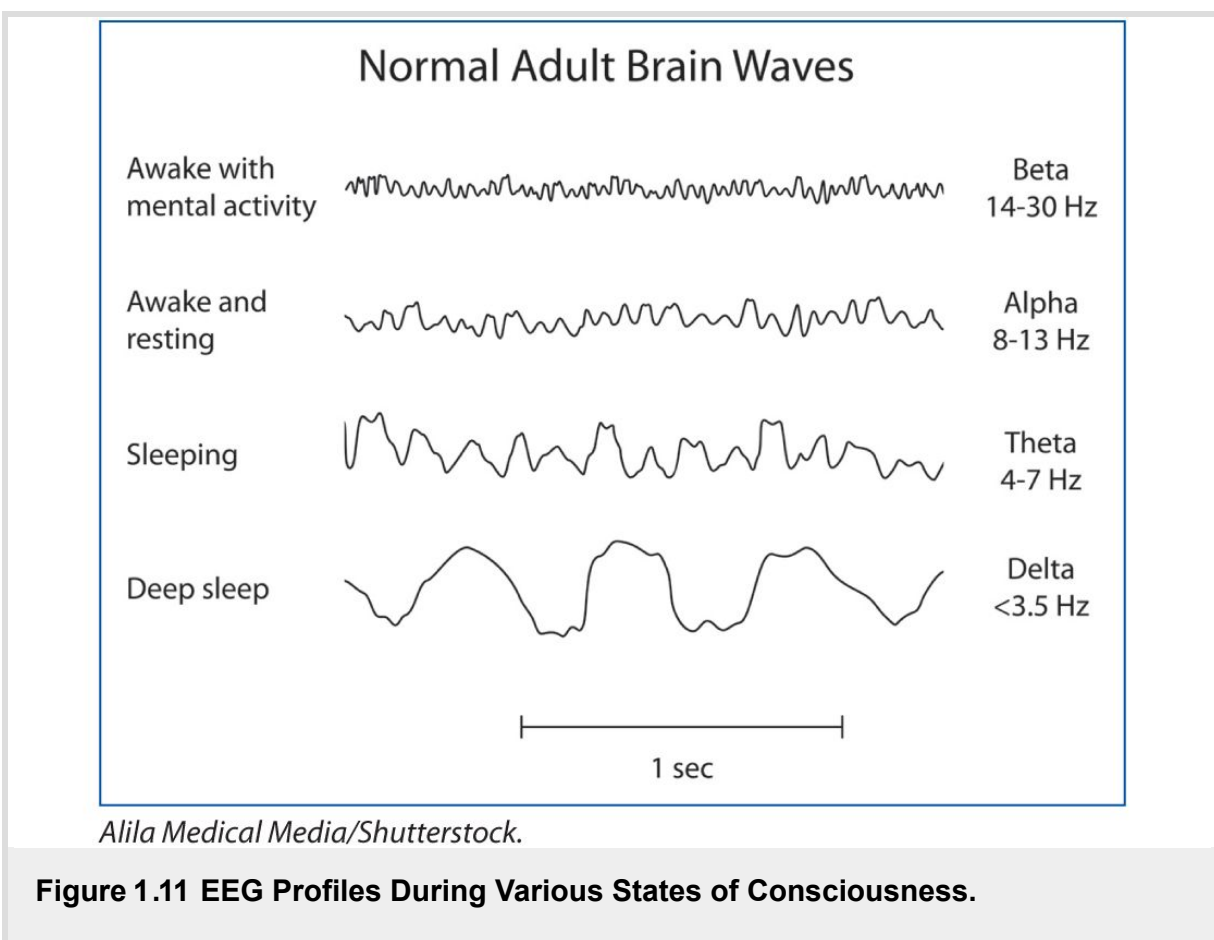
Until relatively recently, the principal basis for understanding the role of the brain in human cognition has been the study of patient populations. We have already described some of this research, such as that with split-brain patients and with patients who have suffered damages to brain areas that cause language deficits. It was research with patient populations such as these that showed that the brain is

lateralized, with the left hemisphere specialized for language processing. Such hemispheric specialization does not occur in other species.

In recent decades, there have been major advances in noninvasive methods of imaging the functioning of the brains of normal participants engaged in various cognitive activities. These advances in neural imaging are among the most exciting developments in cognitive neuroscience and will be referenced throughout this text. Although not as precise as recording from single neurons, which can be done only rarely with humans (and then as part of surgical procedures), these methods have achieved dramatic improvements in precision.

[Electroencephalography \(EEG\)](#) records the electric potentials that are present on the scalp. When large populations of neurons are active, this activity will result in distinctive patterns of electric potential on the scalp. In the typical methodology, a participant wears a cap of many electrodes. The electrodes detect rhythmic changes in electrical activity and record them on electroencephalograms. [Figure 1.11](#) illustrates some recordings typical of various cognitive states. When EEG is used to study cognition, the participant is asked to respond to some stimulus, and researchers are interested in discovering how processing this stimulus impacts general activity on the recordings. To eliminate the effects not resulting from the stimulus, many trials are averaged, and what remains is the activity produced by the stimulus. For instance, [Kutas and Hillyard \(1980\)](#)

found that there was a large dip in the activity about 400 ms after participants heard an unexpected word in a sentence (this is discussed further in [Chapter 13](#)). Such averaged EEG responses aligned to a particular stimulus are called [event-related potentials \(ERPs\)](#). ERPs have very good temporal resolution, but it is difficult to infer the location in the brain of the neural activity that is producing the scalp activity.



Description

Awake with mental activity: The wavelength of the wave is very short and the crests and troughs fluctuate rapidly. The corresponding frequency of the wave is beta 14 to 30 Hertz. Awake and resting: The wavelength of

the wave is low and the crests and troughs occur less rapidly. The corresponding frequency of the wave is alpha 8 to 13 Hertz. Sleeping: The wavelength of the wave is medium and the crests and troughs are irregular. The corresponding frequency of the wave is theta 4 to 7 Hertz. Deep sleep: The wavelength of the wave is high and the crests and troughs are very gradual, almost equal to each other. The corresponding frequency of the wave is delta less than 3.5 Hertz.

There has been a great deal of research on the use of EEG for brain–computer interfaces for applications such as helping paralyzed patients control external devices ([Lotte et al., 2018](#)). Its noninvasive nature makes it a more attractive option than approaches that involve implanting electrodes in the brain. While laboratory EEG systems can be expensive and cumbersome, there are now relatively inexpensive portable systems that approach the sensitivity of laboratory systems. A typical test application involves having a patient move a computer cursor to the left or right by imagining left or right hand movements, which can be readily distinguished in the EEG signal. One application involved flying a toy helicopter ([Doud, Lucas, Pisansky, & He, 2011](#) — see video at [Powell, 2013](#)). The hope is that these EEG methods could be extended to enable control of devices such as wheelchairs, to input text on a computer, and to initiate calls on a telephone.

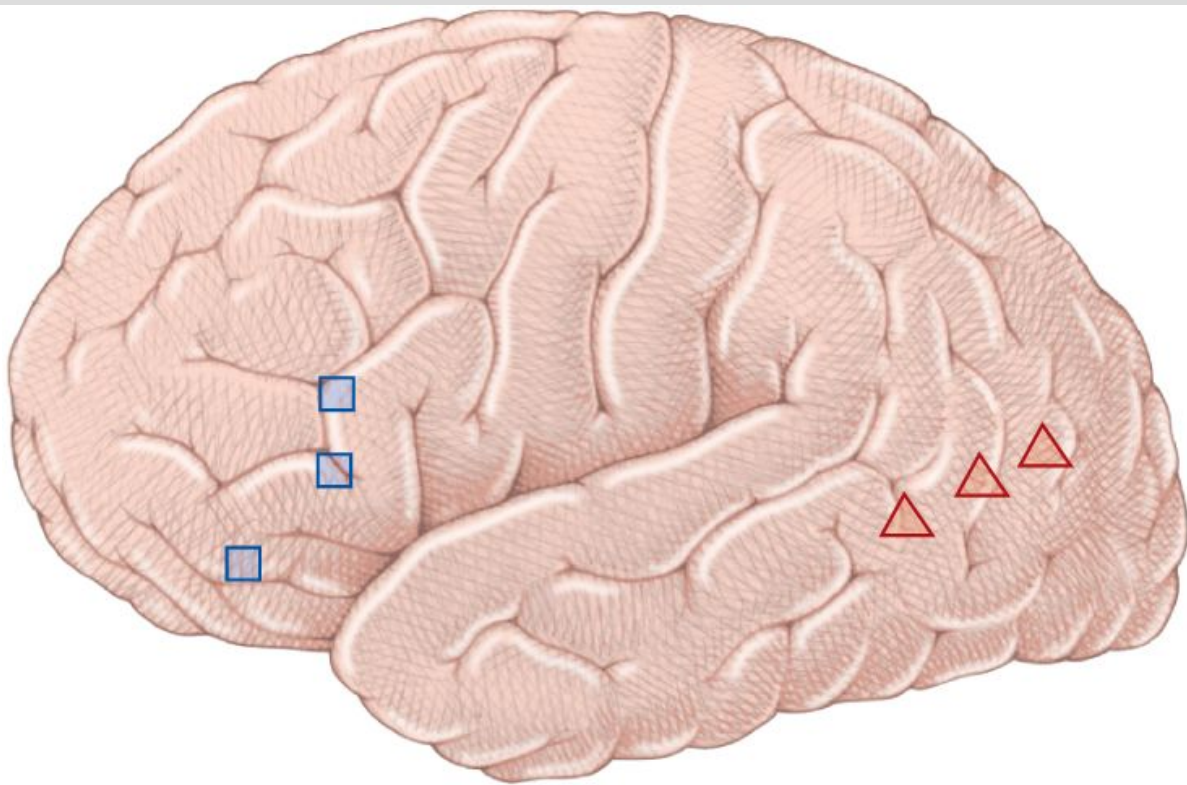
A recent variation of EEG that offers better spatial resolution is [magnetoencephalography \(MEG\)](#), which records magnetic fields produced by the brain's electrical activity. Because of the nature of

the magnetic fields it measures, MEG is best at detecting activity in the sulci (creases) of the cortex and is less sensitive to activity in the gyri (bumps) or activity deep in the brain. However, like many imaging methods, MEG requires expensive equipment, making it appropriate for scientific research but not for practical applications.

Two other methods, [positron emission tomography \(PET\)](#) and [functional magnetic resonance imaging \(fMRI\)](#), provide relatively good information about the location of neural activity but rather poor information about the time course of that activity. Neither PET nor fMRI measures neural activity directly. Rather, they measure metabolic rate or blood flow in various areas of the brain, relying on the fact that more active areas of the brain require greater metabolic expenditures and have greater blood flow. PET and fMRI scans can be conceived as measuring the amount of work a brain region does.

In PET, a radioactive tracer is injected into the bloodstream (the radiation exposure in a typical PET study is equivalent to two chest X rays and is not considered dangerous). Participants are placed in a PET scanner that can detect the variation in concentration of the radioactive element. Current methods allow a spatial resolution of 5 to 10 mm. For instance, [Posner, Peterson, Fox, and Raichle \(1988\)](#) used PET to localize the various components of the reading process by looking at what areas of the brain are involved in reading a word. [Figure 1.12](#) illustrates their results. The triangles on the cortex represent areas that were active when participants were just passively looking at concrete nouns. The squares represent areas

that became active when participants were asked to engage in the semantic activity of thinking of uses for these nouns. The triangles are located in the occipital lobe; the squares, in the frontal lobe. Thus, the data indicate that the processes involved in visually perceiving a word take place in a different part of the brain from the processes involved in thinking about the meaning of a word.



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Research from Posner et al., 1988.

Figure 1.12 Using PET to Determine the Location of Neural Activity. Triangles mark locations in the lateral aspect of the cortex that were activated by the passive visual task of reading a word; squares mark the locations activated by the semantic task of thinking about the meaning of the word.

Description

Three squares are marked on the frontal lobe just above the temporal lobe. Two triangles are marked on the occipital lobe just behind the temporal lobe and one triangle is close to the border of the temporal lobe before the occipital lobe.

The fMRI methodology has largely replaced PET. It offers even better spatial resolution than PET and is less intrusive. fMRI uses the same MRI scanner that hospitals now use as standard equipment to image various structures, including patients' brain structures. With minor modification, it can be used to image the functioning of the brain. fMRI does not require injecting the participant with a radioactive tracer but relies on the fact that there is more oxygenated hemoglobin in the blood in regions of greater neural activity. (One might think that greater activity would use up oxygen, but the body responds to effort by overcompensating and increasing the oxygen in the blood — this is called the [hemodynamic response](#).) Radio waves are passed through the brain, and these cause the iron in the hemoglobin to produce a local magnetic field that is detected by magnetic sensors surrounding the head. Thus, fMRI offers a measure of the amount of energy being spent in a particular brain region: The signal is stronger in areas where there is greater activity. Among its advantages over PET are that it allows measurement over longer periods because there is no radioactive substance injected and that it offers finer temporal and spatial resolution. In the next section I will describe an fMRI study in detail to illustrate the basic methodology and what it can accomplish.

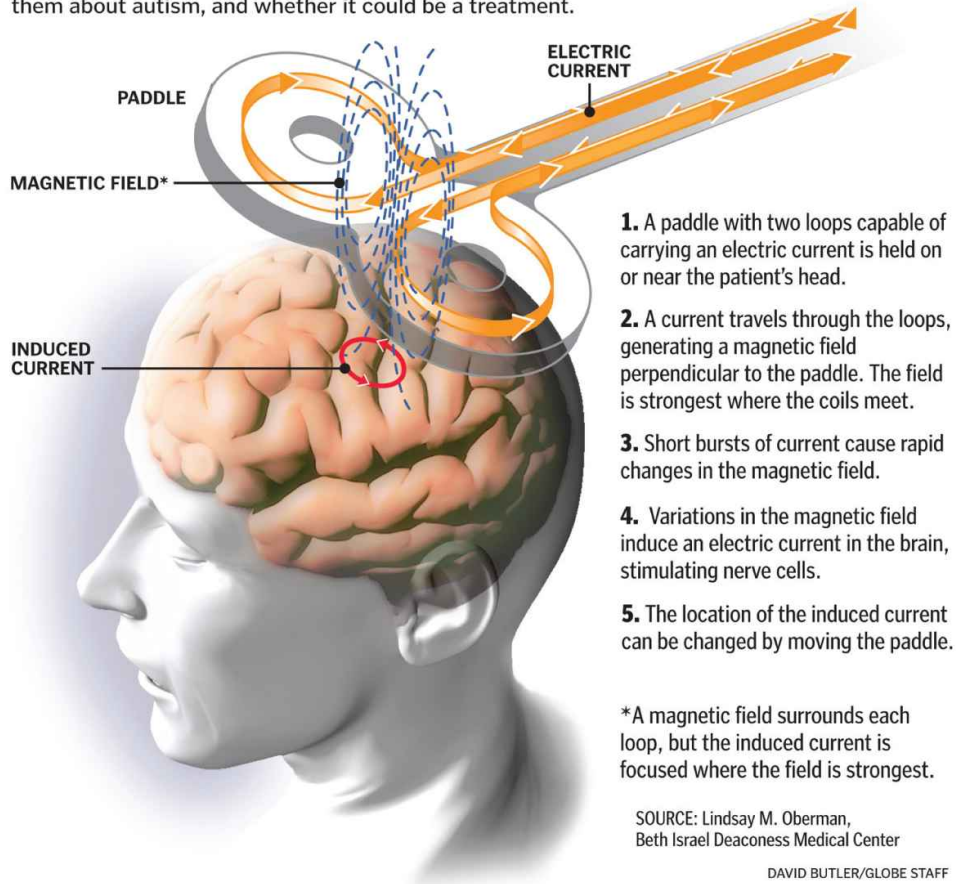
Neither PET nor fMRI is what one would call a practical, everyday measurement method. The more common method, fMRI, uses multimillion-dollar scanners that require the participant to lie motionless in a noisy and claustrophobic space. A related and more practical option is near-infrared sensing ([Strangman, Boas, & Sutton, 2002](#)). This methodology relies on the fact that light penetrates tissue (put a flashlight to the palm of your hand to demonstrate this) and is reflected back. In near-infrared sensing, light is shined on the skull, and the instrument senses the spectrum of light that is reflected back. It turns out that near-infrared light tends not to be absorbed by oxygenated tissue, and so by measuring the amount of light in the near-infrared region (which is not visible to human eyes), one can detect the oxygenation of the blood in a particular area of the brain. This methodology is cheaper and less confining than PET or fMRI and does not require movement restriction. Even now it is used with young children who cannot be convinced to remain still and with Parkinson's patients who cannot control their movements. A major limitation of this technique is that it can only detect activity 2 or 3 cm into the brain because that is as far as the light can effectively penetrate.

These various imaging techniques have revolutionized our understanding of the brain activity underlying human cognition, but they have a limitation that goes beyond temporal and spatial resolution: They provide only a limited basis for causal inference. Activity in a region of the brain during a task does not necessarily mean that the region is critical to the execution of the task. Until

recently, researchers had to study patients with strokes, brain injuries, and brain diseases to get some understanding of how critical a region is. However, methods are now available that allow researchers to briefly incapacitate a region. Principal among these methods is [transcranial magnetic stimulation \(TMS\)](#), in which a coil is placed over a particular part of the head and a magnetic pulse or pulses are delivered to the underlying region of the brain to disrupt the processing there (see [Figure 1.13](#)). If properly administered, TMS is safe and has no lasting effect. It can be very useful in determining the role of different brain regions. For instance, imaging techniques reveal activity in both prefrontal and parietal regions during study of an item that a participant is trying to remember. Nonetheless, the fact that TMS to the prefrontal region ([Rossi et al., 2001](#)) and not the parietal region ([Rossi et al., 2006](#)) disrupts memory formation implies a more critical role for the prefrontal region in memory formation.

How transcranial magnetic stimulation works

Researchers are exploring what the noninvasive technique can teach them about autism, and whether it could be a treatment.



Boston Globe/Getty Images.

Figure 1.13 Transcranial Magnetic Stimulation. TMS is delivered by a coil on the surface of the head, which generates brief but powerful magnetic pulses that induce a temporary current that disrupts neural processing in a small area on the surface of the brain with high temporal and fair spatial precision. This can provide evidence for how critical activity in a given area is for particular brain functions.

Description

An infographic shows a person's head with the brain highlighted within over which a paddle is held. Electric current flows through the paddle which induces current on the brain which is represented by counterclockwise rotating red arrows. A magnetic field is created which is represented by dashed lines. A note corresponding to magnetic field

reads, a magnetic field surrounds each loop, but the induced current is focused where the field is strongest. Text above the illustration reads, researchers are exploring what the noninvasive technique can teach them about autism, and whether it could be a treatment. Process: Step 1: A paddle with two loops capable of carrying an electric current is held on or near the patient's head. Step 2: A current travels through the loops, generating a magnetic field perpendicular to the paddle. The field is strongest where the coils meet. Step 3: Short bursts of current cause rapid changes in the magnetic field. Step 4: Variations in the magnetic field induce an electric current in the brain, stimulating nerve cells. Step 5: The location of the induced current can be changed by moving the paddle.

Techniques such as EEG, MEG, PET, fMRI, near-infrared sensing, and TMS allow researchers to study the neural basis of human cognition with a precision starting to approach that available in animal studies.

Using fMRI to Study Equation Solving

Most brain-imaging studies have looked at relatively simple cognitive tasks, as is still true of most research in cognitive neuroscience. A potential danger of such research is that we will come to believe that the human mind is capable only of the simple tasks that are studied. However, it is possible to use brain imaging to study more complex processes. For example, I will describe a study using fMRI — for which I was one of the researchers ([Qin, Anderson, Silk, Stenger, & Carter, 2004](#)) — that looked at equation solving by children aged 11

to 14 when they were just learning to solve equations. This research illustrates the profitable marriage of information-processing analysis and cognitive neuroscience techniques.

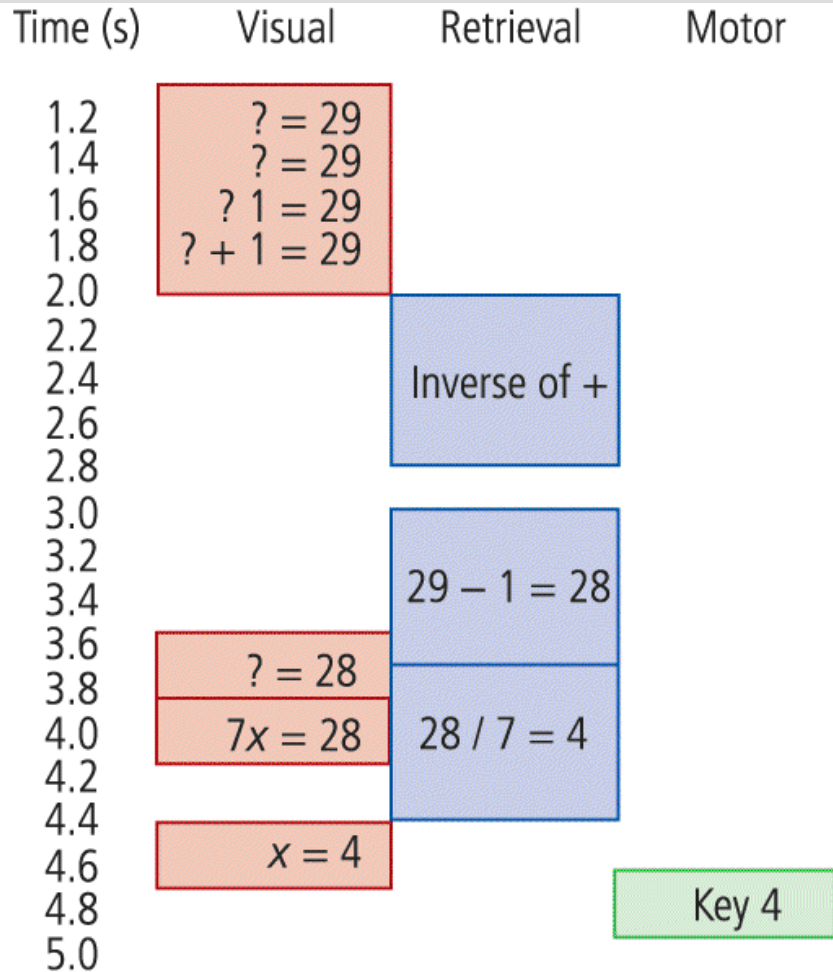
We studied eighth-grade students as they solved equations at three levels of complexity in terms of the number of steps required to transform the equation to find the solution:

0 steps required:	$1x + 0 = 4$
1 step required:	$3x + 0 = 12$ or $1x + 8 = 12$
2 steps required:	$7x + 1 = 29$

Note that the 0-steps equation is rather unusual, with the 1 in front of the x and the $+ 0$ after the x . This format reflects the fact that the visual complexity of different conditions must be controlled to avoid obtaining differences in the visual cortex and elsewhere just because a more complex visual stimulus has to be processed. Students kept their heads motionless while being scanned. They wore a response glove and could press a finger to indicate the answer to the problem (thumb = 1, index finger = 2, middle finger = 3, ring finger = 4, and little finger = 5).

We developed an information-processing model for the solution of such equations that involved imagined transformations of the equations, retrieval of arithmetic and algebraic facts, and programming of the motor response. [Figure 1.14](#) shows the sequencing of these activities. In line with existing research, we would expect that:

1. Programming of the hand would be reflected in activation in the left motor and somatosensory cortex. (See [Figure 1.10](#); participants responded with their right hands, and so the left cortex would be involved.)
2. The imagined transformations of each equation would activate a region of the left parietal cortex involved in mental imagery (see [Chapter 4](#)).
3. The retrieval of arithmetic and algebraic information would activate a region of the left prefrontal cortex (see [Chapters 6 and 7](#)).



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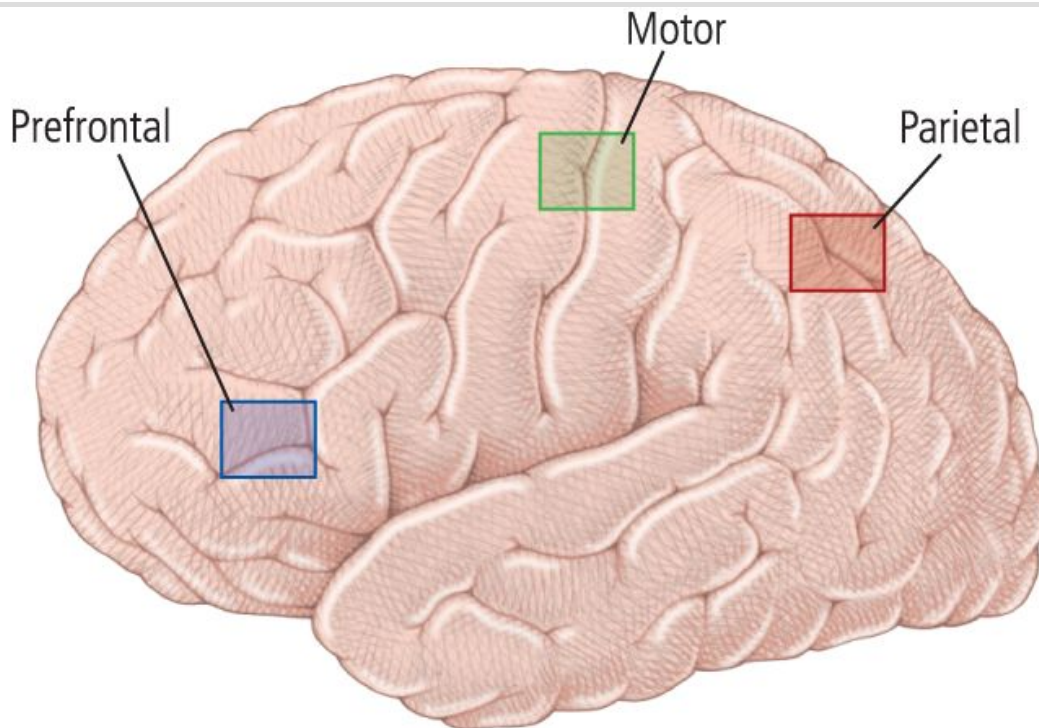
Figure 1.14 The Steps of an Information-Processing Model for Solving the Equation $7x + 1 = 29$. The model includes imagined transformations of the equation (visual processing), retrieval of arithmetic and algebraic facts, and programming of the motor response.

Description

The chart has four columns, the headers read, time in seconds, visual, retrieval, and motor. The time ranges from 1.2 to 5.0 in increments of 0.2 in seconds and serves as a row header. The data for visual is as follows: time-1.2, question mark equals 29; time-1.4, question mark equals 29; time-1.6, question mark 1 equals 29; time-1.8, question mark plus 1

equals 29; time-3.8, question mark equals 28; time-4.0, 7 times x equals 28; time-4.6, x equals 4. The data for retrieval is as follows: time-2.2 to 2.6, inverse of plus; time-3.0 to 3.6, 29 minus 1 equals 28; time 3.8 to 4.4, 28 over 7 equals 4. The data for motor is as follows, time-4.8, key 4.

Figure 1.15 shows the locations of these three regions of interest. Each region is a cube with sides of approximately 15 mm. fMRI is capable of much greater spatial resolution, but the application within this study did not require this level of accuracy.



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Figure 1.15 Regions of Interest for the fMRI Scan in the Equation-Solving Experiment. The imagined transformations would activate a region of the left parietal cortex; the retrieval of arithmetic and algebraic information would activate a region of

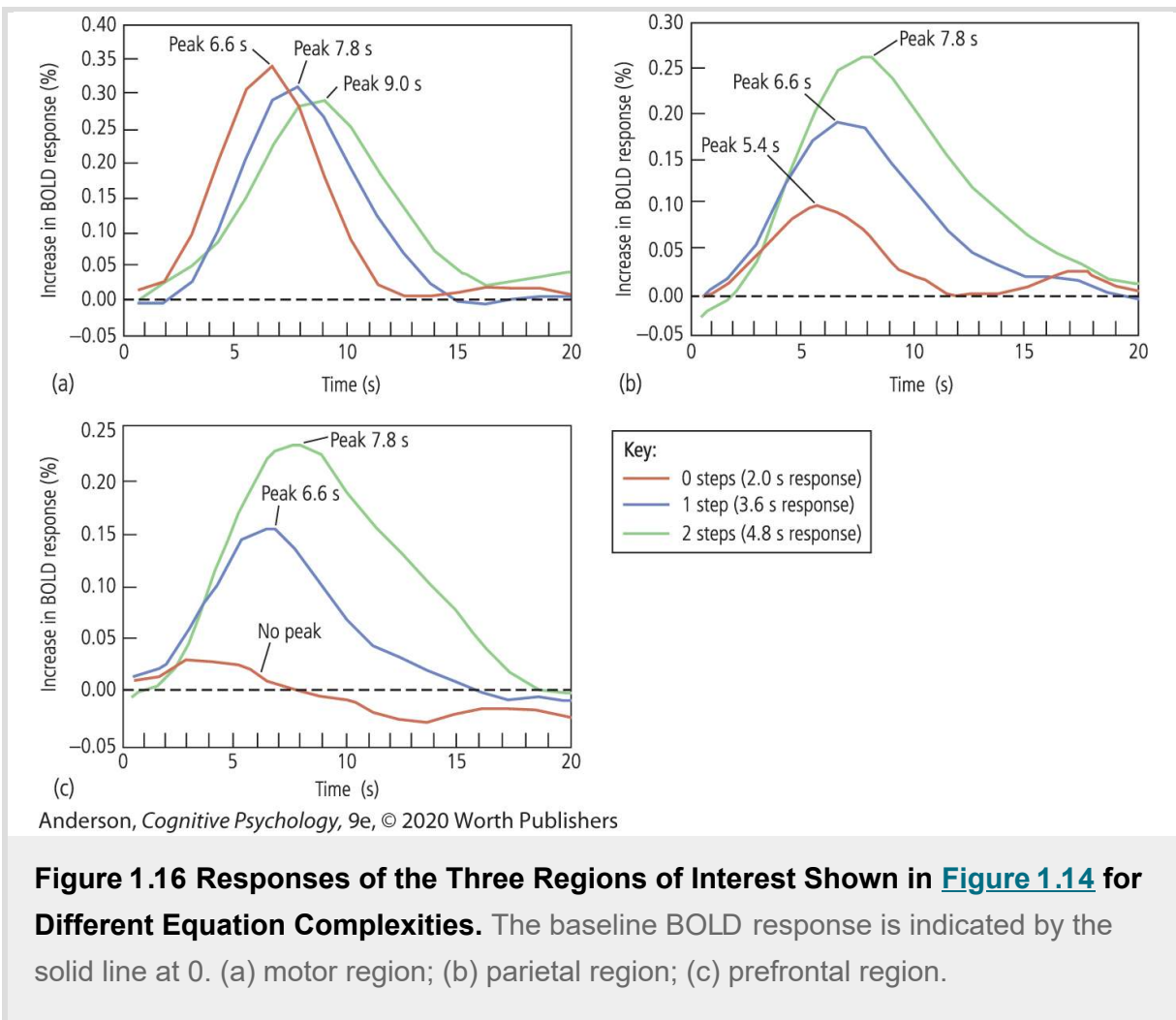
the left prefrontal cortex; and the programming of the hand's movement would activate the left motor and somatosensory cortex.

Description

A small region on the anterior part of the frontal lobe is labeled prefrontal. A small region in the middle point of the superior is labeled motor. A small region on the posterior lobe is labeled parietal.

The times required to solve the three types of equation were 2.0 s for 0 steps, 3.6 s for 1 step, and 4.8 s for 2 steps. However, after students pressed the appropriate finger to indicate the answer, a long rest period followed to allow brain activity to return to baseline for the next trial. Data were obtained in terms of the percentage increase over this baseline of the blood oxygen level dependent response (BOLD response). In this particular experiment, a brain scan was taken every 1.2 s to obtain a reading of the BOLD response. Figure 1.16a shows the BOLD response in the motor region for the three conditions. The percentage increase is plotted from the time the equation was presented. Even though students solved the problem and keyed the answer to the 0-steps equation in an average of 2 s, the BOLD function did not begin to rise above baseline until the third scan after the equation was solved, and it did not reach peak until after approximately 6.6 s. This result reflects the fact that the hemodynamic response to a neural activity is delayed because it takes time for the oxygenated blood to arrive at the corresponding location in the brain. Basically, the hemodynamic response reaches a peak about 4 to 5 s after the event. In the motor

region (see [Figure 1.16a](#)), the BOLD response for a 0-steps equation reached a peak at approximately 6.6 s, for a 1-step equation at approximately 7.8 s, and for a 2-step equation at approximately 9.0 s. Thus, the point of maximum activity reflects events that were happening about 4 to 5 s previously.



Description

The horizontal axis labeled time in seconds ranges from 0 to 20 in increments of 5. The vertical axis labeled increase in BOLD response in percentage ranges from negative 0.05 to 0.40 in increments of 0.5. A key

reads as follows: orange line, 0 step (2.0 seconds response); blue line, 1 step (3.6 seconds response); and green line, 2 steps (4.8 seconds response). Motor region: The orange line starts at (1, 0.01), gradually increases, reaches the peak point at (6.6, 0.33), then gradually decreases to the point (13, 0.005), and again slowly increases and decreases and ends at (20, 0.00). The blue line starts at (0.9, negative 0.005), slightly moves to the right and gradually rises, reaches the peak point at (7.8, 0.30), then falls to the point (15, negative 0.005), slightly moves to the right, then rises again and ends at (20, 0.005). The green line starts at (1, 0.00), gradually rises, reaches the peak point at (9.0, 0.29), then gradually falls to the point (16, 0.025), then increases and ends at (20, 0.05). The orange line reaches peak at 6.6 seconds, the blue line at 7.8 seconds, and the green line at 9.0 seconds. Parietal region: The orange line starts at (0.5, 0.00), gradually increases, reaches the peak point at (5.4, 0.09), then gradually decreases to the point (12, 0.00), then slightly moves to the right, and again slowly increases and decreases and ends at (20, negative 0.01). The blue line starts at (0.4, 0.00), gradually rises, reaches the peak point at (6.6, 0.19), then falls and ends at (20, negative 0.005). The green line starts at (0.5, negative 0.025), gradually rises, reaches the peak point at (7.8, 0.26), then gradually falls and ends at (20, 0.02). The orange line reaches peak at 5.4 seconds, the blue line at 6.6 seconds, and the green line at 7.8 seconds. Prefrontal region: The orange line starts at (0.3, 0.01), slightly rises to the point (3, 0.03), then falls to the point (14.9, negative 0.03), then rises and ends at (20, negative 0.2). The blue line starts at (0.2, 0.01), gradually rises, reaches the peak point at (6.6, 0.15), then falls to the point (17, negative 0.01), and slightly rises and ends at (20, negative 0.01). The green line starts at (0.1, negative 0.01), gradually rises, reaches the peak point at (7.8, 0.23), then gradually falls and ends at (20, negative 0.005). The orange line has no peak, the blue line peaks at 6.6 seconds, and the green line at 7.8 seconds.

The BOLD function allows one to read the brain and see *when* the activity took place (at the peak of the function) and the *amount* of activity that took place (the height of the function at the peak). Note that the functions for motor activity in [Figure 1.16a](#) are of approximately equal height in the three conditions because it takes the same amount of effort to program the finger press, independent of the number of transformations needed to solve the equations.

[Figure 1.16b](#) shows the BOLD responses in the parietal region. Like the responses in the motor region, they peaked at different times, reflecting the differences in time to solve the equations. They peaked a little earlier, however, because the BOLD responses reflected the transformations being made to the mental image of the equation, which occurred before the response was emitted. Also, the BOLD functions reached very different heights, reflecting the different number of transformations that needed to be performed to solve the equation. [Figure 1.16c](#) shows the BOLD responses in the prefrontal region, which were quite similar to those in the parietal region, but with the important difference that there was no rise in the function in the 0-steps condition because it was not necessary to retrieve any information in that condition. Students could just read the answer from the mental representation of the original equation.

This experiment showed that researchers can separately track different information-processing components involved in performing a complex task. The fMRI methodology is especially appropriate for the study of complex cognition. Its temporal resolution is not very

good, and so it is difficult to study in detail very brief tasks such as the Sternberg paradigm (see [Figures 1.1](#) and [1.2](#)). On the other hand, when a task takes many seconds, it is possible to distinguish the timing of processes, as we see in [Figure 1.16](#). Because of its high spatial resolution, fMRI is able to separate out different components of the overall processing. For brief cognition, EEG is often a more appropriate brain-imaging technique because it can achieve much finer temporal resolution.

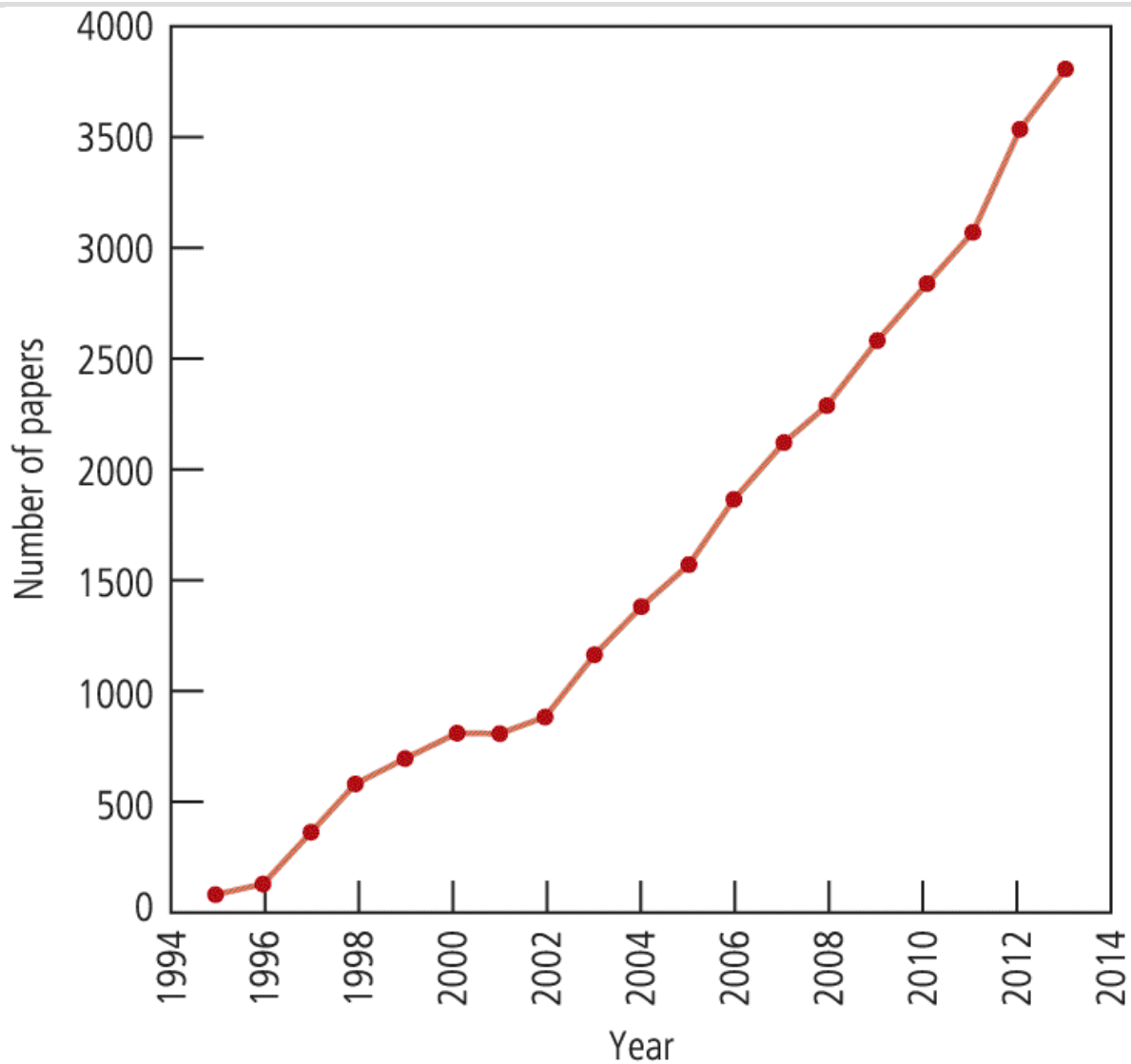
fMRI allows researchers to track activity in the brain corresponding to different information-processing components of a complex task.

A Cognitive Neuroscience Revolution?

The developments that we have reviewed in cognitive neuroscience have coalesced into a new attitude: that the understanding of human cognition must involve reference to brain processes. [McClelland and Ralph \(2015\)](#) note that cognitive neuroscience has begun to make dramatic inroads into the field of cognitive psychology, where many leading investigators have redirected their research to exploit ideas and methods from neuroscience. [Kriegeskorte \(2015\)](#) reviews the changes that have moved the field from the early information-processing work of a half century ago (e.g., as illustrated by [Figure 1.2](#)) that made no reference to brain processes to the point of view that such references are a necessary part of cognitive theory.

An important aspect of this changing point of view is the increasing use of neural imaging techniques by many researchers in cognitive psychology. For instance, the number of fMRI studies has increased by a factor of 100 over two decades ([Bandettini, 2014](#)) (see [Figure 1.17](#)), changing how we think about cognition. While such studies have brought new knowledge, their influence on current thinking has been greater than that new knowledge would imply. Research has shown that neuroscience data make psychological theories more persuasive even when the neuroimaging evidence actually is irrelevant to the theory ([Hopkins, Weisberg, & Taylor, 2016](#)). Also, worth considering is the fact that neuroimaging methods are better suited to understanding simpler cognitive processes than more

complex ones. As a consequence, there has been a change in the kinds of issues being investigated, perhaps to the detriment of our understanding the nature of that intelligence that makes humans unique among animals.



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Data from Bandettini, 2014.

Figure 1.17 Increasing Use of fMRI in Psychology Research. The number of papers published each year involving studies using fMRI rose dramatically in the two decades 1995–2014.

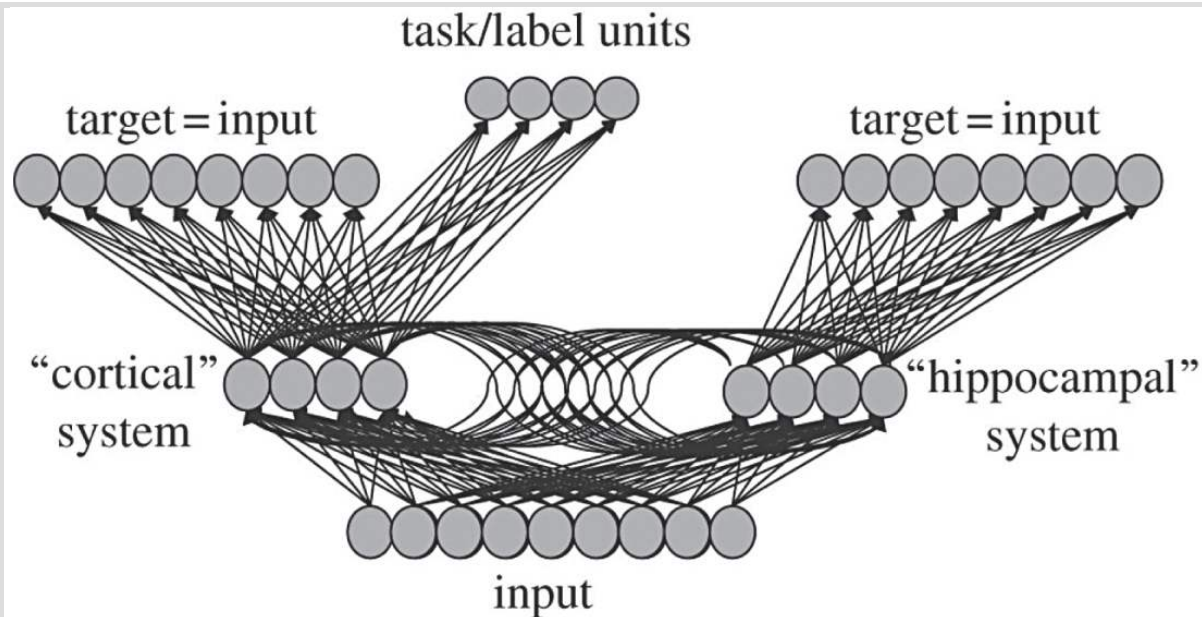
Description

The years range from 1994 to 2014 in increments of 2. The number of papers ranges from 0 to 4000 in increments of 500. The curve in the graph passes through the following points: (1995, 100), (1996, 150), (1997, 400), (1998, 550), (1999, 700), (2000, 800), (2001, 750), (2002, 850), (2003, 1200), (2004, 1400), (2005, 1500), (2006, 1900), (2007, 2100), (2008, 2250), (2010, 2500), (2011, 2850), (2012, 3000), (2013, 3500), (2013, 3900).

More research in psychology is now aimed at trying to understand the function of a particular brain structure. For instance, a current focus of research is understanding how regions of the temporal lobe become specialized for face recognition and word reading (e.g., [Nestor, Plaut, & Behrmann, 2011](#); [Ozernov-Palchik et al., 2018](#)), as opposed to understanding face recognition and word reading as cognitive processes. In part, this focus has been promoted by government funding decisions. For instance, in 2013 President Obama announced the BRAIN Initiative (Brain Research through Advancing Innovative Neurotechnologies), which would provide support for both increased neural recording and new technologies for neural recording.

On the theoretical side, there has been a continuing debate about the value of theories that make no reference to the brain (e.g., [Griffiths, Chater, Kemp, Perfors, & Tenenbaum, 2010](#); [McClelland et al., 2010](#)). It is argued that explanations of cognitive function should

be in terms of computations like those the brain performs. Such explanations are often described as [connectionist models](#). A majority of computational models in the premier theoretical journal in psychology, *Psychological Review*, are connectionist models. A connectionist theory focuses on the connections between neuron-like elements. These connections have properties like those associated with synapses. For instance, [Figure 1.18](#) ([Westermann & Mareschal, 2014](#)) shows a network of such elements used in a model of how children learn to label objects such as cats. The circles represent neural elements and the arrows represent connections among them. The input elements take on different patterns of activation thought to be like patterns of neural activation. Activation in elements can excite and inhibit activity in other elements that they are connected to, like activity in one neuron can change the activity in other neurons it synapses on. The behavior of these elements is simulated on computers, and the simulated behavior is remarkably humanlike. While these elements do not behave in detail like real neurons, they have general properties that are similar to the general properties of real neurons. In particular, they can change the strengths of connections among neural elements and thereby “learn” in ways that are thought to be similar to the process of neural learning.



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Figure 1.18 A Connectionist Model of How Perceptual Input Results in

Categorical Labels. The nodes (circles) represent neuron-like elements, and the arrows represent connections with properties like synapses. The “perceptual” input at the bottom (start) of the process connects to elements in a hippocampus-like system, for targeted “memory” of the input, and to elements in a cortex-like system, for targeted “interpretation” of the input, which is then labeled as belonging to the task category.

Description

All nodes are arranged horizontally. Nine nodes at the bottom of the model are labeled input. Four nodes above and to the left are labeled cortical system and four nodes above and to the right are labeled hippocampal system. Each of both sets of four nodes are connected to each of the eight input nodes. Two sets of eight nodes labeled target equals input are above each system of four nodes. Each of the eight node sets connect to each of the corresponding system. Four nodes at the center top are labeled task/label units and each node connects to each cortical system node.

There has been a huge surge of interest from artificial intelligence in what is called **deep learning** ([LeCun, Bengio, & Hinton, 2015](#); [Marcus, 2018](#)). This involves learning connections in networks that have many more layers of connecting neuron-like elements than does the network shown in [Figure 1.18](#). Deep learning systems have been shown to be capable of greater accuracy than humans in recognizing objects (see the discussion of object recognition in [Chapter 2](#)). The AlphaGo system mentioned earlier in this chapter was a deep learning system. These systems are often so complex with their many layers that it seems impossible to understand what they are actually doing, but nonetheless one cannot argue with their success. This raises the possibility that human cognition may be similarly too complex to really understand, and this issue has led to a new research area, explainable artificial intelligence ([Gunning, 2017](#)), which attempts to develop methods to help us understand how such systems actually work. It is sort of like trying to develop a cognitive psychology theory for artificial intelligence artifacts.

Research involving brain imaging and connectionist models of neural processing is changing the current understanding of the nature of cognition.

Chapter Review

Questions for Thought

Each chapter ends with a set of “Questions for Thought,” designed to emphasize the core issues in the field. For this chapter, consider the following questions:

1. Research in cognitive psychology has been described as “the mind studying itself.” Is this really an accurate characterization of what cognitive psychologists do in studies like those illustrated in [Figure 1.1](#) and in [Figures 1.14–1.16](#)? Does the fact that cognitive psychologists study their own thought processes create any special opportunities or challenges? Is there any difference between the scientific study of a mental system such as memory and the scientific study of a bodily system such as digestion?
2. Notable figures such as Elon Musk, Bill Gates, and Stephen Hawking have warned of the danger that systems displaying artificial intelligence will eventually become superintelligent and replace the human race. Does this seem more likely if we assume that deep learning approaches will continue to produce ever more successful systems with underlying processing that cannot be understood by humans?
3. The scientific program of reductionism tries to reduce one level of phenomena into a lower level. For instance, this chapter has discussed how complex economic behavior can be reduced to the decision making (cognition) of individuals and how this can be reduced to the actions of individual neurons in the brain. But reductionism does not stop there. The activity of neurons can be reduced to chemistry, and chemistry can be reduced to physics. When does it help and when does it not help to try to understand one level in terms of a lower level? Why is it silly to go all the way in a reductionist program and attempt something like explaining economic behavior in terms of particle physics?
4. Humans are frequently viewed as qualitatively superior to other animals in terms of their intellectual function. What are some ways in which humans seem to display such qualitative superiority? How would these

features of human cognition create problems in generalizing research from other animals to humans?

5. New techniques for imaging brain activity have had a major impact on research in cognitive psychology, but each technique has its limitations. What are the limitations of the various techniques? What would be the properties of an ideal brain-imaging technique? How do studies that actually go into the brain (almost exclusively done with nonhumans) inform the use of brain imaging?
6. What are the ethical limitations on the kinds of research that can be performed with humans and nonhumans?

Key Terms

This chapter has introduced quite a few key terms, most of which will reappear in later chapters:

[action potential](#)

[amygdala](#)

[aphasia](#)

[artificial intelligence \(AI\)](#)

[axon](#)

[basal ganglia](#)

[behaviorism](#)

[blood oxygen level dependent response \(BOLD response\)](#)

[Broca's area](#)

[cerebral cortex](#)

[cognitive neuroscience](#)

[cognitive psychology](#)

[cognitive revolution](#)

[cognitive science](#)

connectionist models

corpus callosum

deep learning

dendrites

dualism

electroencephalography_(EEG)

empiricism

event-related potentials_(ERPs)

excitatory synapses

frontal lobe

functional magnetic resonance imaging_(fMRI)

Gestalt psychology

gyrus

hemodynamic response

hippocampus

information-processing approach

inhibitory synapses

intelligence

introspection

linguistics

magnetoencephalography_(MEG)

nativism

neocortex

neuron

neurotransmitters

occipital lobe

parietal lobe

positron emission tomography_(PET)

[prefrontal cortex](#)

[p-value](#)

[rate of firing](#)

[replicability crisis](#)

[split-brain patients](#)

[Sternberg paradigm](#)

[sulcus](#)

[synapse](#)

[temporal lobe](#)

[topographic organization](#)

[transcranial magnetic stimulation \(TMS\)](#)

[Wernicke's area](#)

Notes

¹ Weisberg (1986) comes to a similar conclusion.

² Neurons are by no means the majority of cells in the nervous system. There are many other cell types, such as glial cells, whose main function is thought to be supportive of the neurons.

³ The term “cerebral cortex” is widely used to refer just to the neocortex, and I have largely adopted that usage in this book, as well as using just “cortex” as a short way of referring to the cerebral cortex or neocortex. In places where the distinction is important, I have used the more specific “neocortex.”



Chapter 2 Perception



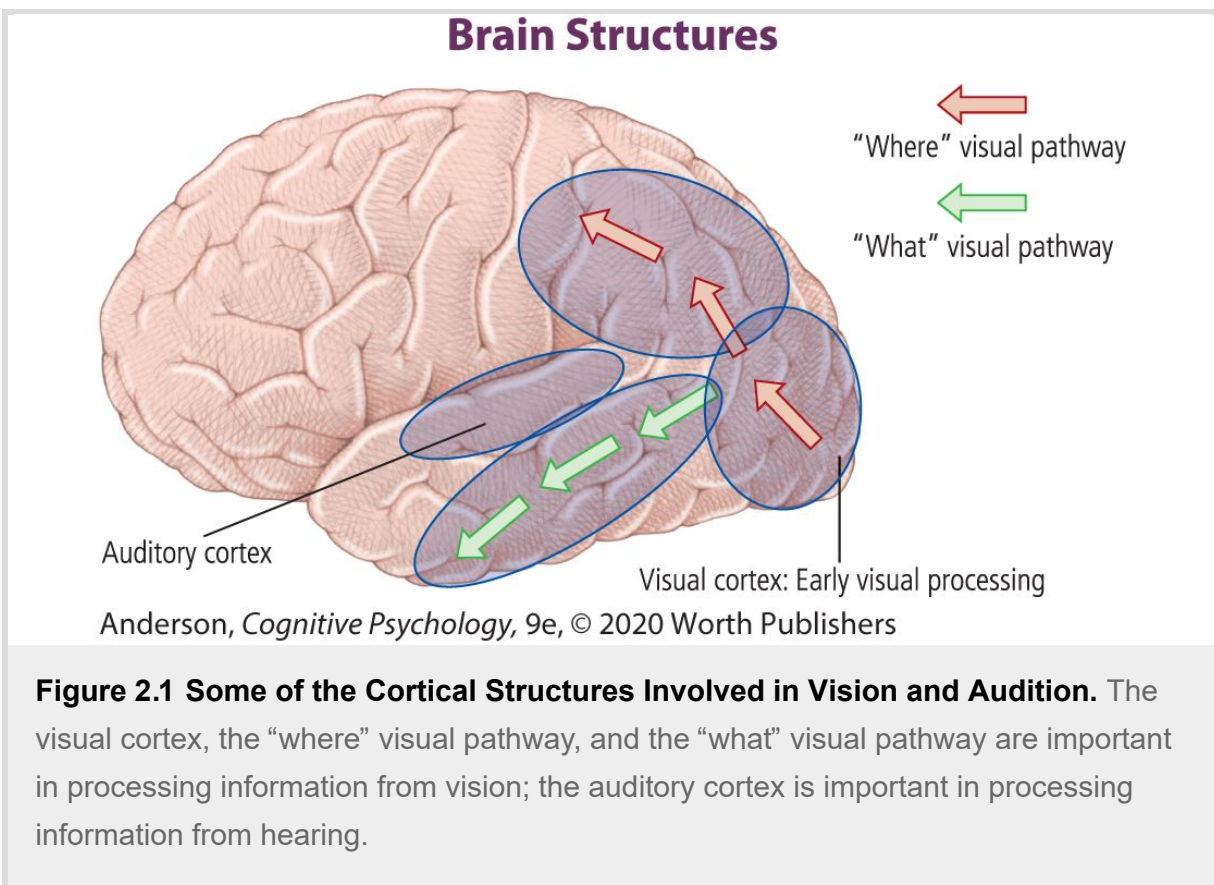
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Our bodies are bristling with sensory receptors — neurons that detect sights, sounds, smells, and physical contact. Billions of neurons process sensory information and deliver what they find to the higher centers in the brain. This chapter will focus on visual perception and, to a lesser extent, on audition as it is involved in the perception of speech — the two most important perceptual systems for the human species. The chapter will address the following questions:

- How does the brain extract information from the visual signal?
- How is visual information organized into objects?
- How are the sounds of speech (phonemes) recognized?
- How are visual and speech patterns recognized?
- How does context affect pattern recognition?

Visual Perception in the Brain

Humans have a big neural investment in processing visual information. This is illustrated in [Figure 2.1](#), which shows some of the cortical structures devoted to processing information from vision and hearing. This investment in vision is part of our “inheritance” as primates, which have evolved to devote as much as 50% of their brains to visual processing ([Barton, 1998](#)). The enormous investment underlies the human ability to see the world.



Description

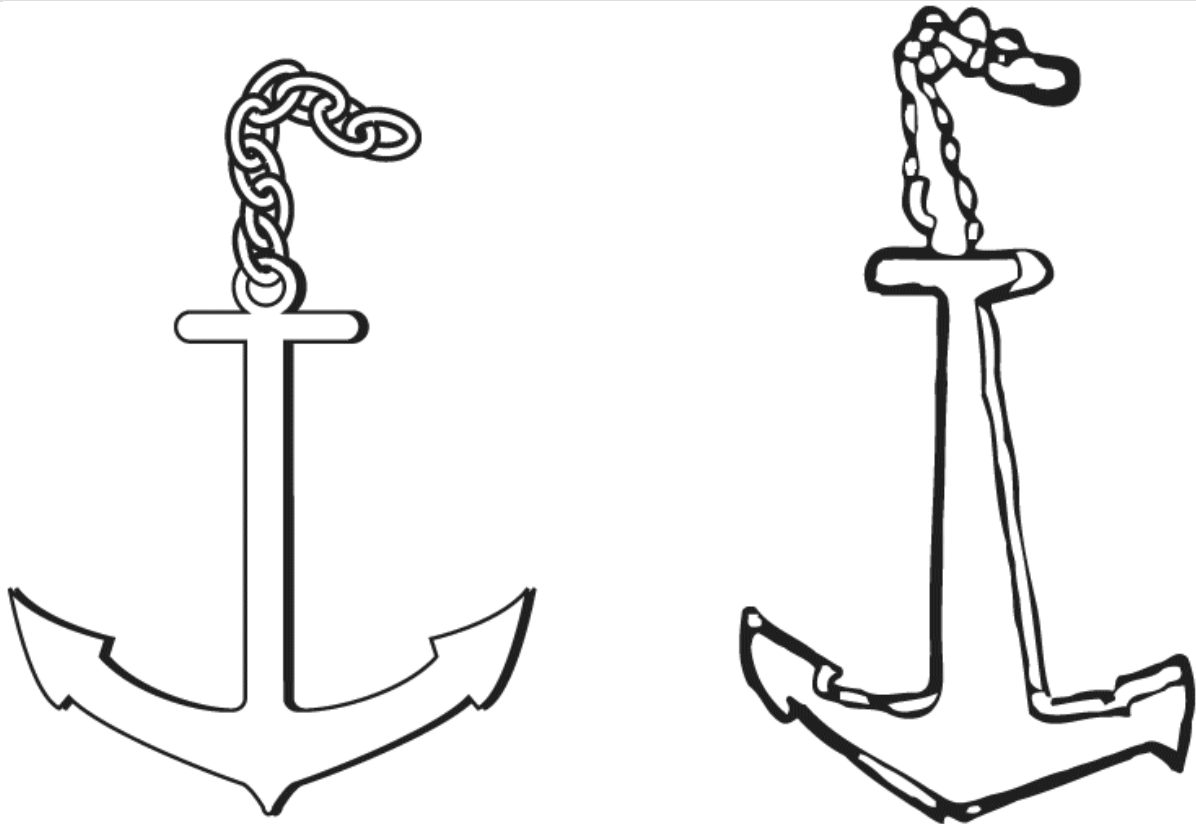
An area located superior of the temporal gyrus in the temporal lobe is labeled auditory cortex. An area located to the posterior of the brain is

labeled visual cortex: early visual processing. Green arrows that start at top of temporal lobe and move towards the bottom center represent open quotes what close quotes visual pathway. Red arrows that start from the posterior of the occipital lobe, move upward toward the parietal lobe represents open quotes where close quotes visual pathway.

This is vividly demonstrated by individuals with damage to certain brain regions who are not blind but are impaired at recognizing things visually, a condition called [visual agnosia](#). One case of visual agnosia involved a soldier who suffered brain damage resulting from accidental carbon monoxide poisoning. He could recognize objects by their feel, smell, or sound, but he was unable to distinguish a picture of a circle from that of a square or to recognize faces or letters ([Benson & Greenberg, 1969](#)). On the other hand, he was able to discern light intensities and colors and to tell in what direction an object was moving. Thus, his sensory system was still able to register visual information, but the damage to his brain resulted in a loss of the ability to transform visual information into perceptual experience. This case shows that perception is much more than simply the registering of sensory information.

Generally, visual agnosia is classified as either [apperceptive agnosia](#) or [associative agnosia](#) (for a review, read [Farah, 1990](#)). Patients with apperceptive agnosia, like the soldier just described, are unable to recognize simple shapes such as circles or triangles, or to draw shapes they are shown. Patients with associative agnosia, in contrast, are able to recognize simple shapes and can

successfully copy drawings, even of complex objects. However, they are unable to recognize complex objects, even after copying drawings of them. [Figure 2.2](#) shows the original drawing of an anchor and a copy of it made by a patient with associative agnosia ([Ratcliff & Newcombe, 1982](#)). Despite being able to produce a relatively accurate drawing, the patient could not recognize this object as an anchor (he called it an umbrella). Patients with apperceptive agnosia are generally believed to have problems with early processing of information in the visual system. In contrast, patients with associative agnosia are thought to have intact early processing but to have difficulties with pattern recognition, which occurs later. This chapter will first discuss the early processing of information in the visual stream and then the later processing of this information.



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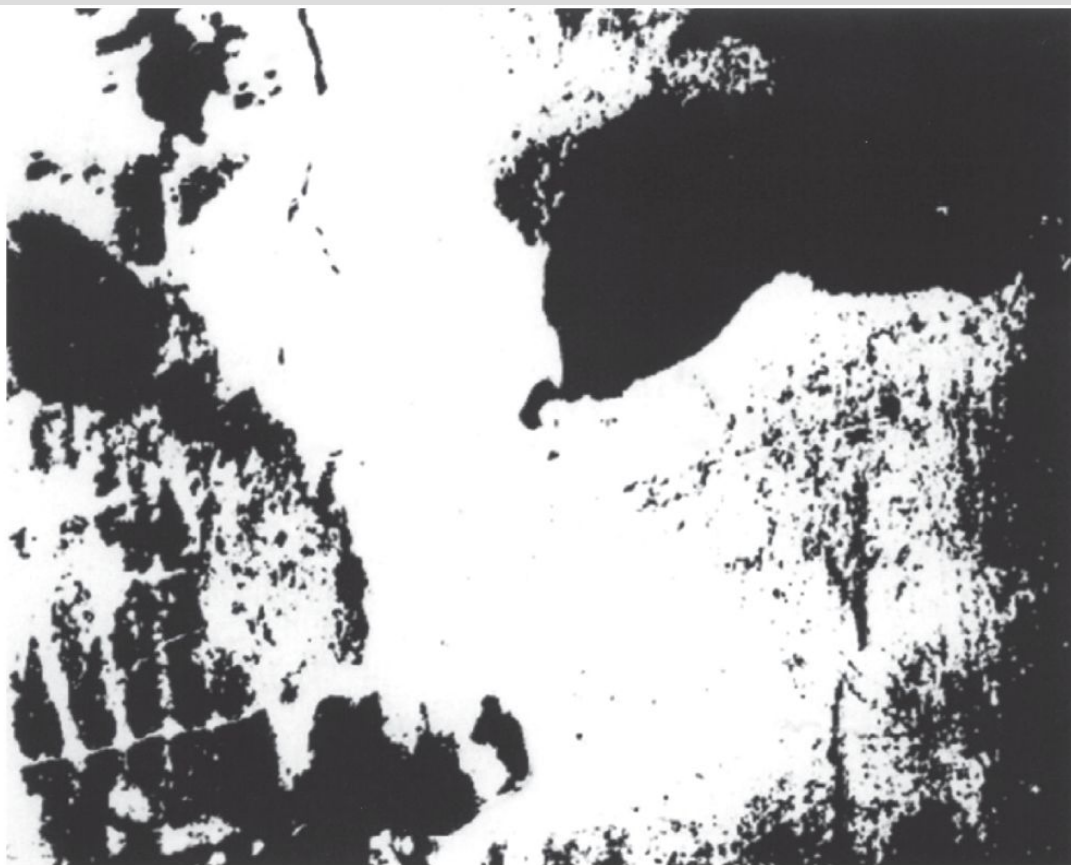
Figure 2.2 Effects of Associative Agnosia. A patient with associative agnosia was able to copy the original drawing of the anchor at left (his drawing is at right), but he was unable to recognize the object as an anchor.

Description

The drawing of the anchor on the left is symmetrical and accurate, while the drawing of the anchor on the right is asymmetrical and inaccurate.

Figure 2.3 offers an opportunity for a person with normal perception to appreciate the distinction between early and late visual processing. If you have not seen this image before, it will strike you

as just a bunch of ink blobs. You will be able to judge the size of the various blobs and reproduce them, just as Ratcliff and Newcombe's patient could, but you will not see any patterns. If you keep looking at the image, however, you may be able to make out a cow's face (nose slightly to the left of center at the bottom). Now your pattern perception has succeeded, and you have interpreted what you have seen.



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Figure 2.3 Early vs. Late Visual Processing. A scene in which we initially perceive just black and white areas; only after looking at it for some time is it possible to make out the face of a cow.

Description

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Visual perception can be divided into an early phase, in which shapes and objects are extracted from the visual scene, and a later phase, in which the shapes and objects are recognized.

Early Visual Information Processing

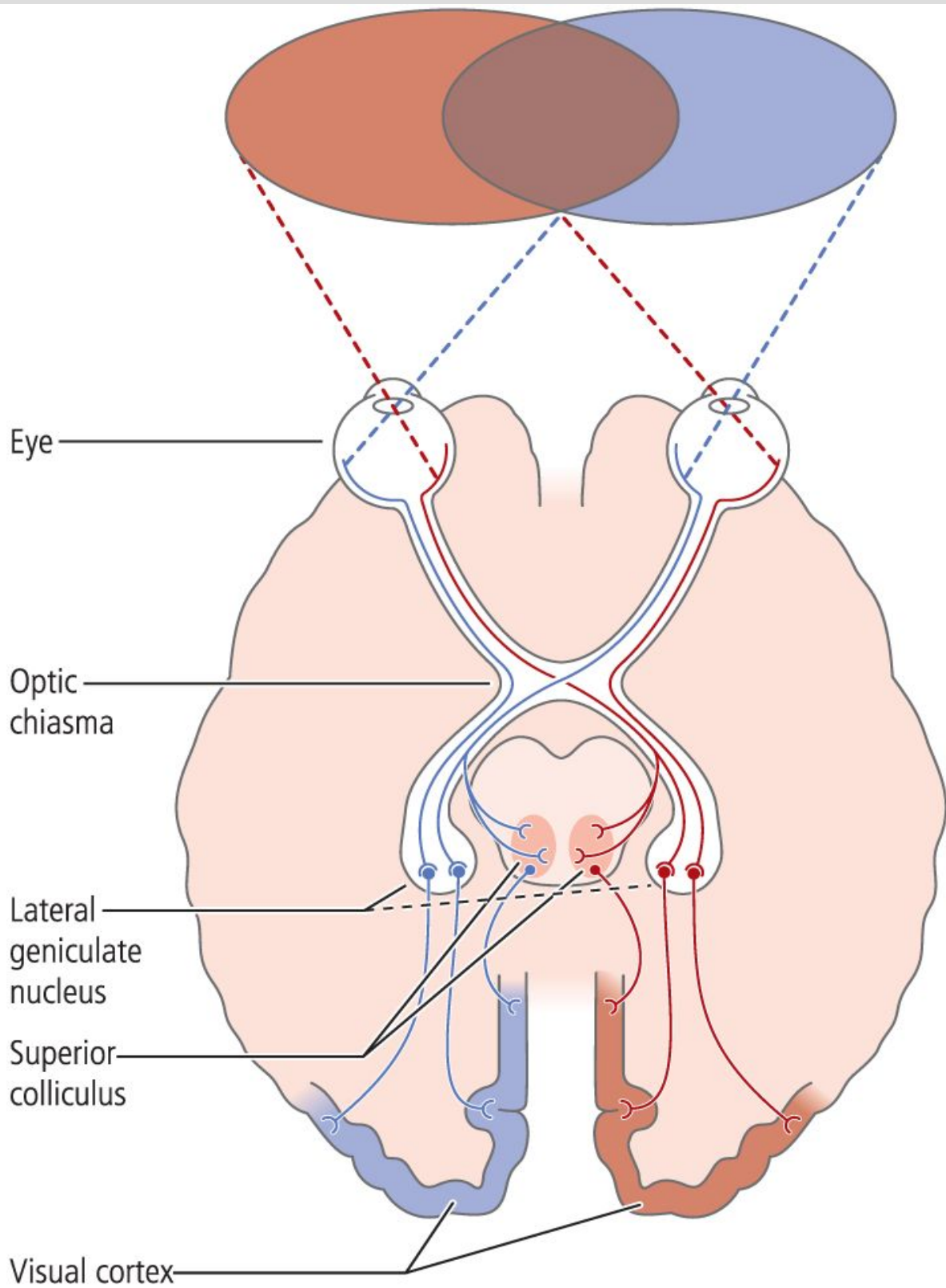
Early visual information processing begins in the eye. Light coming through the eye falls on the [retina](#), the innermost layer of cells within the eye. Photoreceptor cells in the retina contain light-sensitive molecules that undergo structural changes when exposed to light, initiating a photochemical process that converts light into neural signals. There are two distinct types of photoreceptors in the eye: [cones](#) and [rods](#). Cones are involved in color vision and produce high resolution (i.e., greater visual acuity). Less light energy is required to trigger a response in the rods, but they produce poorer resolution and no information about color. As a consequence, they are principally responsible for the less acute, black-and-white vision we experience at night. Cones are especially concentrated in a small area of the retina called the [fovea](#). When we focus on an object, we move our eyes so that the image of the object falls on the fovea, which enables us to take full advantage of the high resolution of the cones in perceiving the object. Foveal vision detects fine details,

whereas vision in the rest of the visual field — the periphery — detects more global information, including movement.

The photoreceptor cells synapse onto bipolar cells and these onto ganglion cells, whose axons leave the eye and form the optic nerve, which goes to the brain. Altogether there are about 800,000 ganglion cell axons in the optic nerve of each eye. Each ganglion cell encodes information from a small region of the retina called the cell's [receptive field](#). Typically, the amount of light stimulation in that region of the retina is encoded by the neural firing rate on the ganglion cell's axon.

[Figure 2.4](#) illustrates the neural pathways from the eyes to the brain. The optic nerves from the eyes meet at the optic chiasma, where the ganglion cell axons from the insides of the retinas (the sides nearest the nose) cross over and go to the opposite side of the brain (axons from the inside of the left eye go to the right side of the brain, and axons from the inside of the right eye go to the left side of the brain). The axons from the outsides of the retinas continue to the same side of the brain as the eye from which they emanate. This means that the right halves of both eyes are connected to the right hemisphere and the left halves to the left hemisphere. As [Figure 2.4](#) illustrates, the lens focuses light from the left side of the visual field onto the right half of each eye and light from the right half of the visual field onto the left half of each eye. Thus, information about the left side of the visual field goes to the right brain, and information about the right side of the visual field goes to the left brain. This is one instance of

the general fact, discussed in [Chapter 1](#), that the left hemisphere processes information about the right part of the world and the right hemisphere processes information about the left part.



Anderson, *Cognitive Psychology*, 9e, © 2020 Worth Publishers