CHAPTER

7 Executive Processes

Learning Objectives

You're on your own in the kitchen, preparing some pasta for dinner, music blasting in the background. The phone rings. It's a friend who wants you to do him a favor tomorrow and pick up a package when you're downtown. As you continue the conversation, your eyes go back to the stove and focus on the water to be sure that it's not boiling yet. Still chatting, you try to figure out how you'll fit your friend's errand into everything else you have to do downtown. Whoops, the water's boiling, and you realize you haven't started to heat the sauce—you blew it. Too many things to do going on at once!

To avoid domestic and social disaster in this situation—a ruined dinner, rudeness to your friend—in these few minutes you have to do five distinct things, some of them simultaneously: pay attention to getting the meal together, switch your attention to the phone call and continue to switch back and forth between phone and stove, ignore the background music while listening to your friend, plan how to schedule tomorrow's activities so as to include your

friend's request, and monitor how the cooking is going. As you deal with the situation, at least five critical cognitive processes are in play:

- *The kind of selective attention that typically acts on the contents of working memory and directs subsequent processing so as to achieve some goal.* (You're focusing on tomorrow's schedule, which you've entered into working memory.) This kind of attention—often called **executive attention**—is to be distinguished from the kind that selects certain spatial positions in the outside world and determines what gets perceived in the first place (which is discussed in Chapter 3, *Attention*).
- *Switching executive attention from one activity, or process, to another* (from watching the pot to answering the phone).
- *Ignoring or inhibiting information that has already been perceived.* (Yes, you've been hearing the music—but now you hear it less while your friend is talking.)
- *Scheduling a sequence of activities.* (Can you postpone a planned coffee date for half an hour to give you time to make it downtown and back to campus?)
- *Monitoring your performance.* (How are you doing with that pot of salted water—will it never boil?).

These five processes are referred to as *executive processes;* the term comes from Alan Baddeley's (1986) influential model of working memory in which there are separate short-term storage systems for verbal and visual information and a central executive that operates on the contents in storage (discussed in Chapter 6, *Working Memory*). Executive processes organize our mental lives, just as a corporate executive coordinates a business's activities; in both cases the function is administrative, not "hands on." The corporate executive may reallocate resources to increase the size of the service department in the interest of improving quality control, but the actual repairs are made at a lower organizational level. Like the CEO, executive processes coordinate lower level processes (such as remembering words and adding numbers). If the phone rang right now, you'd be able to turn readily from the process of reading this line to the process of answering your phone because the executive process "switching attention" organizes the two activities.

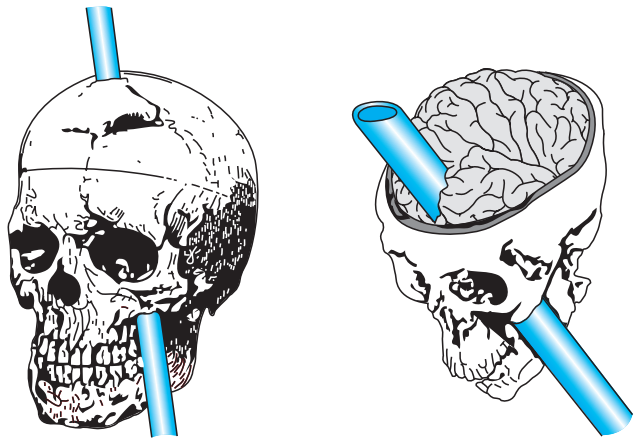
More formally, we may define **executive processes** as processes that modulate the operation of other processes and that are responsible for the coordination of mental activity so that a particular goal is achieved. Processes that, like executive processes, operate on other processes are known as *metaprocesses.* (Although all executive processes are metaprocesses, not every metaprocess is an executive one, because it may not coordinate and control mental activity.)

This chapter addresses six questions about executive processes:

1. Are executive processes mediated by the frontal lobes?
2. What is executive attention, and how can it be modeled?
3. What is involved in switching attention?
4. What is response inhibition, and what is distinctive about it?
5. What mechanisms are used for sequencing information?
6. What is involved in monitoring our performance "on line"?

1. THE FRONTAL LOBE CONNECTION

One of the major reasons for thinking that executive processes form a distinct class of cognitive processes comes from relatively early studies of patients who had suffered frontal brain damage as a result of a **closed head injury**, injury caused by an external bump that does not pierce the skull. (Why do car accidents or other head-bumping incidents lead to damage in the frontal lobes more than to other places in the brain? Examine a skull sometime, and you will see that it has ridges on its inside surface; the sharpest and most protruding of these are adjacent to the frontal lobes, so a bang on the skull cuts deeper into the frontal lobes than elsewhere.) Of course, frontal damage can result from other events as well, for instance, from a stroke or from brief deprivations of oxygen. One of the oddest incidents—and most significant in its early influence on thinking about frontal lobe function—resulted from an accident to a railway worker, Phineas Gage, in 1848. Part of Gage's job was to pack explosives into drilled holes with a 3-foot-long rod called a tamping iron. When a charge went off prematurely, the tamping iron was driven into his head, entering below the left cheekbone and exiting through the top of his skull (Figure 7–1), and landing some distance away. Gage survived; but, although he



(a) (b)

FIGURE 7–1 Phineas Gage, frontal-lobe patient

(a) This drawing of the reconstructed path of the tamping iron through Gage's head appeared in the 1868 account of the case by Dr. John M. Harlow, who treated Gage at the time of the accident and examined his skull after his death.

(Harlow, J. M. 1868. Recovery from the passage of an iron bar through the head. *Publ. Mass. Med. Soc.* 2:327–347. Found at: http://home.earthlink.net/~electrikmon/Neuro/artGage.htm)

(b) A modern-day reconstruction, using computer techniques, that shows the areas of the brain that were destroyed. The study of Phineas Gage, who survived the accident and lived for another 13 years, marks the beginning of the systematic analysis of frontal-lobe function.

(H. Damasio, T. Grabowski, R. Frank, A. M. Galaburda and A. R. Damasio (1994). The return of Phineas Gage: The skull of a famous patient yields clues about the brain. *Science, 264,* 1102–1105. Found at: http://www.sciencemuseum.org.uk/exhibitions/brain/291.asp. Reprinted with permission.)

apparently recovered physically and suffered little intellectual damage, his behavior was radically changed. Before his accident he was trustworthy, hardworking, of calm demeanor; after it, he was irresponsible, impulsive, given to fits of temper and profanity. The physician who treated him at the time of the accident and later studied him, John M. Harlow, drew a connection between the area of greatest damage in the frontal lobes and the lack of social restraint that Gage showed subsequently.

In the twentieth century, Hebb and Penfield (1940) were the first to observe some of the most striking facts about frontal-lobe patients. Such patients perform relatively normally on an IQ test, yet are often incapable of leading anything like a normal life. It is as if they have all their cognitive components intact but have lost the ability to organize and control them. The obvious hypothesis was that the frontal lobes implement these control processes—the executive processes—and consequently damage to the frontal lobes leads to a breakdown in executive processes and a breakdown in normal life.

Consider the case of Dr. P., whose history is described in Lezak (1983) and adapted here. Dr. P. was a successful middle-aged surgeon who used the financial rewards of his practice to pursue his passions for traveling and playing sports. While undergoing minor facial surgery, he suffered complications that caused his brain to be deprived of oxygen for a short period. This led to damage in areas of the frontal lobes. This damage had profound negative consequences on his mental functioning, compromising his ability to plan, to adapt to change, and to act independently. Standard IQ tests administered after the surgery revealed Dr. P.'s intelligence still to be, for the most part, in the superior range; yet he could not handle many simple day-to-day activities and was unable to appreciate the nature of his deficits. His dysfunction was so severe that not only was returning to work as a surgeon out of the question, but also his brother had to be appointed his legal guardian. Previously Dr. P. had skillfully juggled many competing demands and had flexibly adjusted to changing situations and demands. Now, however, he was unable to carry out all but the most basic routines and those only in a rigid, inflexible manner. Furthermore, he had lost the ability to initiate actions and the ability to plan. His sister-in-law had to tell him to change his clothes, and his family managed to get him to do this on his own only after years of rule setting. He was able to work as a delivery truck driver for his brother's business, but only because his brother structured the day so that it involved minimal planning. His brother would give him information about one delivery at a time. After each delivery, Dr. P. would call in for directions to the next stop. Dr. P. was totally unaware of his situation. He seemed unconcerned and uninterested in how he was provided with clothes, food, and lodging, and was totally complacent about being a ward of his brother and sister-in-law. Formerly an outgoing man, he now spoke in a monotone and expressed little emotion. He did not initiate any activities or ask questions about his life, and was content to spend his free time watching television.

This is the story of a man in whom executive processes have broken down. Dr. P.'s inability to appreciate the nature of his deficits suggests a breakdown in self-monitoring; his inability to juggle competing demands implicates a deficit in attention-switching. And, most blatant, Dr. P. seemed to have completely lost the

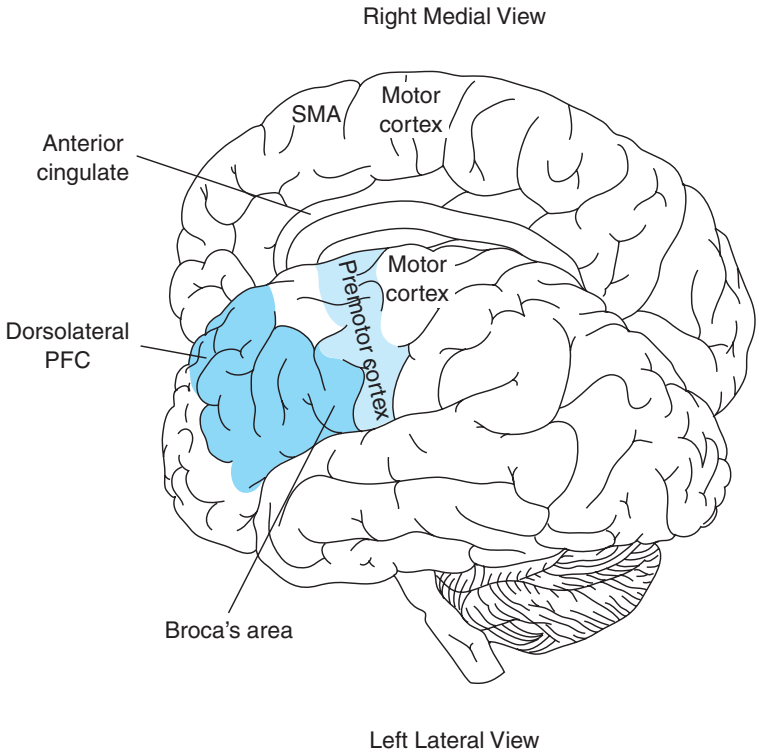


FIGURE 7–2 Frontal lobe syndrome starts here

These views of the brain—a lateral view of the left hemisphere, and behind it a partial medial view of the right hemisphere—show the areas involved: the dorsolateral prefrontal cortex, the anterior cingulate, the premotor area, and, at the posterior end of the prefrontal cortex, Broca's area (note: SMA stands for supplementary motor area, to be discussed in Chapter 11).

(From *Fundamentals of Human Neuropsychology,* 5/e by Bryan Kolb and Ian Q. Wishaw. © 2003 by Worth Publishers. Used with permission.)

ability to sequence activities to achieve a goal. His condition is described as *frontal-lobe syndrome*.

Actually, the brain area involved is not the entire frontal lobe, but only the anterior part of it, the prefrontal cortex (PFC). Figure 7–2 is a simple schematic of the left side of the brain and distinguishes the PFC from the rest of the cortex. The PFC lies directly in front of the motor and supplementary motor areas. At the most posterior end of the PFC is Broca's area, which is known to be involved in speech (as described in Chapter 6). Portions of the premotor area may mingle with true PFC and are sometimes considered to be part of the PFC.

The PFC has many anatomical properties that make it suitable for implementing executive processes. For one thing, it is extremely large in humans, disproportionately so compared to most other primates. This suggests that the PFC may be responsible for some of the more complex activities that humans carry out, such as mentally sequencing a list of activities. For another, the PFC receives

information from virtually all perceptual and motor cortical areas, and a wide range of subcortical structures as well. This mass of connections provides a good infrastructure for combining the diverse sources of information needed for complex behavior. The PFC also has multiple projections back to sensory, cortical, and motor systems that allow it to exert a top-down influence on other neural structures, including those mediating the perception of objects (Miller, 2000).

The idea that every executive process is primarily mediated by the PFC is the **frontal executive hypothesis**. This hypothesis has been widely accepted for a long time, and it has usefully stimulated a great deal of research. It also provides a conceptual framework for thinking that all executive processes are alike in critical ways. As we will see, the hypothesis is overstated, but there is indeed a special connection between executive processes and the frontal lobes.

Comprehension Check:

1. What evidence directly links executive processes to the PFC?
2. What properties of the PFC make it particularly suitable for mediating executive processes?

2. FRONTAL DAMAGE AND THE FRONTAL HYPOTHESIS

A number of tests that are used to diagnose frontal-lobe damage demonstrate the extent of deficits in executive processing. When administered to neurologically healthy people, these tests can also tell us something about the way executive processes work.

Perhaps the best known of these tests is the **Stroop task** (mentioned in Chapter 3), a classic psychological test of attentional function devised in the 1930s by J. Riddley Stroop and still widely used today in various forms (Stroop, 1935) (Figure 7–3). In the standard version the names of colors are presented in colored ink, and the participant's task is to name the ink color and ignore the color name. Sometimes the

BLUE	WHITE
BLACK	GRAY
GRAY	WHITE
BLUE	BLACK

FIGURE 7–3 A Stroop test for a two-color book

For both columns, state the color of the *ink* (don't read the word) as quickly as you can. Did you sense a difference in your performance on the two columns?

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name and print color are *compatible,* as when the word *blue* is printed in that color. At other times the color name and the print color are *incompatible*, as when the word *black* is printed in blue. Remember, the task is to name the *ink color*—so the correct answer in both examples here is "blue." With normal participants, accuracy is high even for incompatible trials, but it takes longer to respond to them than to compatible trials. It is as if participants have to do some extra processing on incompatible trials, but that such processing succeeds. Frontal-lobe patients who have damage to the PFC, particularly the dorsolateral (i.e., upper side) PFC, show a different pattern of results. Their accuracy level on incompatible trials is significantly lower than that of neurologically healthy participants. The standard interpretation of these results is that to succeed in the task, participants must selectively attend to the ink color or inhibit the color name (or both), and frontal participants are known to be impaired in selective attention and inhibition (Banich, 1997). Thus, we have some support for the idea that executive attention and inhibition are executive processes: they are clearly metaprocesses, and they are mediated by the PFC.

A word of caution: there's an intuitive sense in which attention and inhibition go together—it is hard to imagine focusing on something without at the same time ignoring something else. Put another way, it is hard to imagine processing some information without at the same time inhibiting the processing of other information. But can attention and inhibition be considered to arise from the same underlying process? This problem has bedeviled modern cognitive psychology since its inception. In Ulric Neisser's *Cognitive Pyschology* (1967), a classic book that helped define the field, the author pointed out that the act of selective attention could be achieved by focusing on the to-be-attended representation or process, or by inhibiting all irrelevant representations and processes, and it is often difficult experimentally to tell focusing from inhibition. Recent models of executive attention (e.g., Cohen et al., 1996) contain both excitatory and inhibitory components. Although it is useful to begin our discussion with a concept of attention that includes either focusing or inhibitory components, we will later consider cases that clearly require inhibition of response. For now, when we talk of executive attention, keep in mind that inhibition may sometimes be involved as well.

The Wisconsin Card Sort task, illustrated in Figure 7–4, is another well-known test of frontal-lobe damage. Four stimulus cards are arrayed in front of the participant, each bearing a design with a distinctive value on each of three attributes: number, color, and shape (e.g., one white triangle; two bright blue stars; three light blue crosses; four circles of some other color—this text is limited in the number of colors it can present). From a deck of similar cards in which the values differ from those of the four stimulus cards (that is, the values are in different combinations, such as three white circles or one light blue triangle), participants must take each card in turn and match it to one of the stimulus cards. And here's the rub: participants are not told the criterion for matching—whether it is number, color, or shape—but only whether their match is "right" or "wrong." At first participants must guess the critical attribute, but since they receive feedback after every response they eventually home in on the right one. After they have sorted about 10 cards correctly, the examiner changes the critical attribute without warning. Normal participants soon figure out, from the feedback, first that the critical attribute has changed, and then what the new one is.

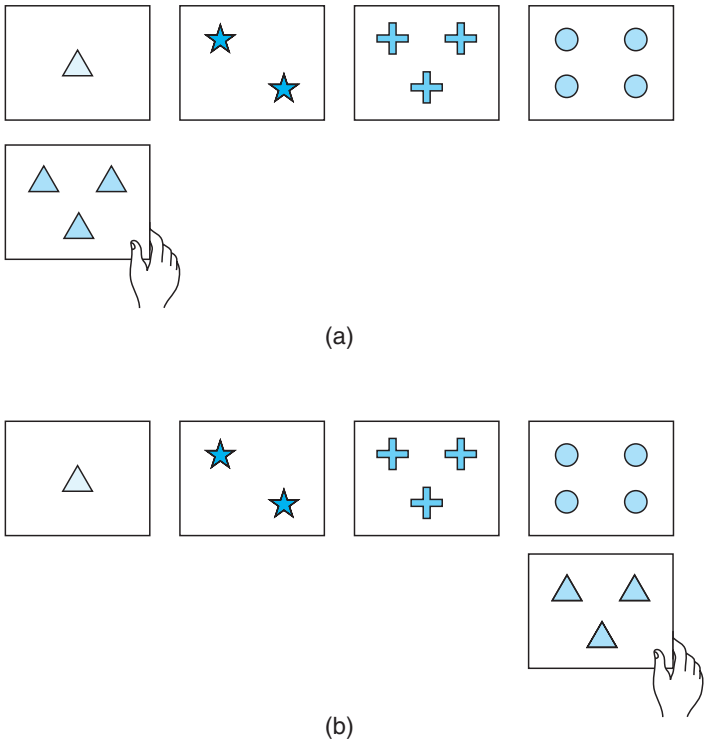


FIGURE 7–4 Two examples of performance on the Wisconsin Card Sort task

In this particular series, the task is to sort on the basis of color. (a) An incorrect sort: the participant is matching the test card on the basis of shape rather than color. (b) A correct sort: the participant is matching the test card on the basis of color rather than shape or number.

(After Banich, Marie T., *Neuropsychology: The Neural Bases of Mental Function.* © 1997 by Houghton Mifflin Company. Used with permission.)

Interestingly, there is no difference between the performance of normal participants and that of frontal (PFC) patients in determining the first critical attribute, but there is a big difference in their ability to switch attributes—an example of switching attention. Normal participants switch critical attributes after a few trials of negative feedback, but frontal patients are far less able to switch attributes, and often keep going for many trials, continuing to sort in accord with the original critical attribute (Banich, 1997). Indeed, there are anecdotal reports of frontal patients who can tell you that the critical attribute has changed, but nevertheless continue to sort on the basis of the original attribute. This suggests that switching attention is another executive process that is compromised by frontal-lobe damage.

There is further systematic evidence that executive attention, inhibition, and attention-switching are involved in performance on frontal-lobe tests (see Miyake et al., 2000). For present purposes, it is sufficient to consider only one further frontal-lobe task, the Tower of Hanoi problem (Figure 7–5). (You might look on the Web for an electronic version of the Tower of Hanoi problem and play a few rounds; what's required in the task quickly becomes obvious.) In its simplest version the task involves

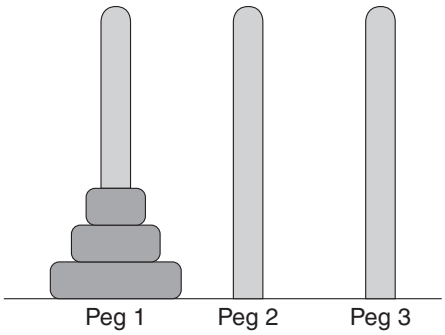


FIGURE 7–5 Three-disk Tower of Hanoi problem

At the outset all the disks are on the first peg, as shown here. The task is to move all the disks to peg 3, with the constraints that only one disk can be moved at a time and that a larger disk can never be placed on a smaller one.

three pegs and three different-size disks. At the outset, all the disks are on peg 1; the participant's task is to move all the disks to peg 3, with the constraints that only one disk can be moved at a time and that a larger disk can never be placed on a smaller one. A further wrinkle: participants are asked to solve the problem "in their head"—no objects to manipulate, no computer version, no paper and pencil. Once they've done this, participants are asked to show their solution (by actually moving the disks, or by the electronic equivalent). Behavioral experiments indicate one of the major strategies used: the participant represents the whole array in working memory, selectively attends to the top disk on peg 1, mentally moves it to peg 3, updates working memory with the new array, then selectively attends to the middle-size disk on peg 1, moves it to peg 2, updates working memory with a new configuration, and so on (e.g., Rips, 1995).

Frontal-lobe patients, particularly patients with damage to the dorsolateral PFC, perform poorly on the Tower of Hanoi problem, taking many more moves than do normal participants to achieve a solution (Shallice, 1982). In relation to executive processes, two points are critical. First, the Tower of Hanoi task involves attending to some disks while ignoring others, as well as switching attention between each mental move and updating working memory; thus, the usual suspects are involved. Second, the task involves goals ("get the big disk to the bottom of peg 3") as well as subgoals ("get the big disk on peg 1 out from under"). Thus, goals are decomposed into subgoals, and a big problem is broken into smaller ones, suggesting that analysis by subgoals and sequencing of steps are also executive processes. (These latter processes will be discussed in Chapter 10.)

We have emphasized patients with direct injuries to the frontal lobes, but other kinds of patient groups also share something of a frontal-lobe syndrome. Although the most dramatic symptom in early Alzheimer's disease (AD) is memory loss, another early symptom is poor performance on frontal-lobe tasks (e.g., Baddeley, 1986). One of the first brain areas affected in AD is the PFC. Thus, AD patients may have frontal-lobe syndrome. Further, many neurologists and neuropsychologists are now observing what they call *executive dysfunction* in children with learning dis-

disabilities and in adults who are markedly disorganized and failing in their careers. The fact that what appear to be the same functions—the executive processes—are all affected in various diseases and disorders provides further evidence that these processes form a distinct class.

Are there other executive processes beyond the five outlined at the beginning of the chapter? Possibly—analysis by subgoals and updating working memory may be viable candidates (see Banich, 1997; Gazzaniga et al., 1998)—but none of these other candidates has been as systematically studied as the five executive processes that we will consider in the remainder of this chapter: executive attention, attention-switching, response inhibition, temporal-coding-plus-sequencing, and monitoring. Furthermore, these five processes appear to be required in many real-life situations.

Comprehension Check:

1. Why is executive attention needed in the Stroop task?
2. What executive processes are needed to perform well on the Tower of Hanoi problem?

3. EXECUTIVE ATTENTION

Executive attention, which directs subsequent processing, is needed whenever multiple mental representations in working memory, or multiple processes operating on representations, compete for the control of cognition and behavior. When you play a game of chess, you attend to various pieces in sequence, as these players are doing in Figure 7–6. When you do a crossword puzzle, you attend to some spaces and

FIGURE 7–6 Executive attention required here

At least for the novices among these players, executive attention is needed at every move of a chess game.

words while inhibiting the others. When you hear an ambiguous sentence, you attend to some meanings while inhibiting others. Indeed, it is difficult to think of a complex mental event that does *not* require executive attention. Executive attention was certainly going on in the kitchen, when you had to attend both to your friend on the phone and your pasta water on the boil.

Executive attention determines which of the contenders will gain control. Let's take another look at the Stroop task of naming the ink color in which a color name is printed, because it is the task par excellence for understanding executive attention. The basic finding for normal participants is that it takes less time to say the print color when the color is compatible with the color name (*red* printed in red ink) than when it is incompatible (*blue* printed in red ink). In essence, when an automatic response (i.e., one that does not require conscious intention, such as saying "red" for the word *red* even when it is printed in blue) must be overcome, some other process must be brought into play so that behavior satisfies the goal. Over the years, many other tasks have been developed that have this character. For example, it is harder to report the color of a pictured banana when that color is anything but yellow (Klein, 1964). The Stroop effect thus applies to noncolor stimuli that, like a picture of a *banana,* refer to objects with a characteristic color.

Now consider a task that's a little further removed from Stroop, a *stimulus–response compatibility task* (Fitts & Deininger, 1954). **Stimulus–response compatibility** is a measure of the degree to which the assignment of the correct response to a stimulus is consonant with the way people would act naturally. The compatibility can be spatial, as in a head-up map (that is, one that is oriented in the same direction as the observer by rotating about its center), or symbolic (such as in using high pitch to signal upward movement and low pitch to signal downward movement).

In a typical version of a task designed to assess stimulus–response compatibility, a stimulus is presented on either the left or right side of a display. In the *compatible* condition, participants respond to the stimulus on the left by pushing a left-sided key, and to a stimulus on the right by pushing a right-sided key. In the *incompatible* condition, the stimulus–response assignments are reversed: now left-sided stimuli go with right-handed responses, whereas right-sided stimuli go with left-handed responses. Stimulus-response assignments are of course more natural in the compatible condition. Response times are faster in the compatible than the incompatible condition (Kornblum & Lee, 1995; Kornblum et al., 1990), a finding that has important safety applications in industrial design (Figure 7–7). This *compatibility effect* is one of the most easily demonstrated phenomena in cognitive psychology. Remarkably, one can get a similar result even when the position of the stimulus is irrelevant. Suppose participants have to make a right-handed response whenever a circle appears and a left-handed response whenever a square appears. Participants respond faster when the object—circle or square—appears on the same side as the required response, even though the object's position is irrelevant to the task (Simon, 1990).

What's going on in these tasks? There is either a relatively automatic connection between stimuli and responses (ink color goes with color name, stimulus position goes with response position) or an arbitrary connection (ink color is arbitrarily associated with a color name, response position is the opposite of stimulus position). When the

FIGURE 7–7 Straighten up and fly right

With complex displays like this, it is important that the stimulus–response assignments, in the positioning of controls and the arrangement of displays, be compatible.

connection is automatic, little executive attention is needed. (Even after his brain damage, Dr. P. could still carry out the most basic routines of surgery; presumably these were the automatic ones.) But when the two sources of information are not compatible, you must attend to the relevant information—"it is color that matters"—and perhaps inhibit the automatic connection. (Dr. P. apparently could not do this. He could carry out routines only in a rigid, inflexible manner.) This attention-and-inhibition amounts to some extra cognitive work, and we are usually aware of having to do it.

3.1. A Neural-Network Model of Conflict in Processing

Most researchers agree with the formulation of attention-and-inhibition described above, but the trick is to spell out the details. In the basic Stroop task, the participant must attend to the ink color and perhaps inhibit the color word. How exactly is this done—what representations and processes are involved? A number of proposals (e.g., Kornblum et al., 1990; Zhang et al., 1999) have been made, but perhaps the most influential one is a neural-network model that has been developed over the years by Jonathan Cohen and colleagues (1990, 1996). It is easier to understand this model if we build it in stages; Figure 7–8 presents the first stage.

This is a relatively simple model—information flows only in an upward direction—with three layers: the input layer, the hidden layer, and the response layer. (Neural-network models are discussed in Chapter 1; see Figure 1–14.) You can think of the nodes as representations, and the connections as associations between the

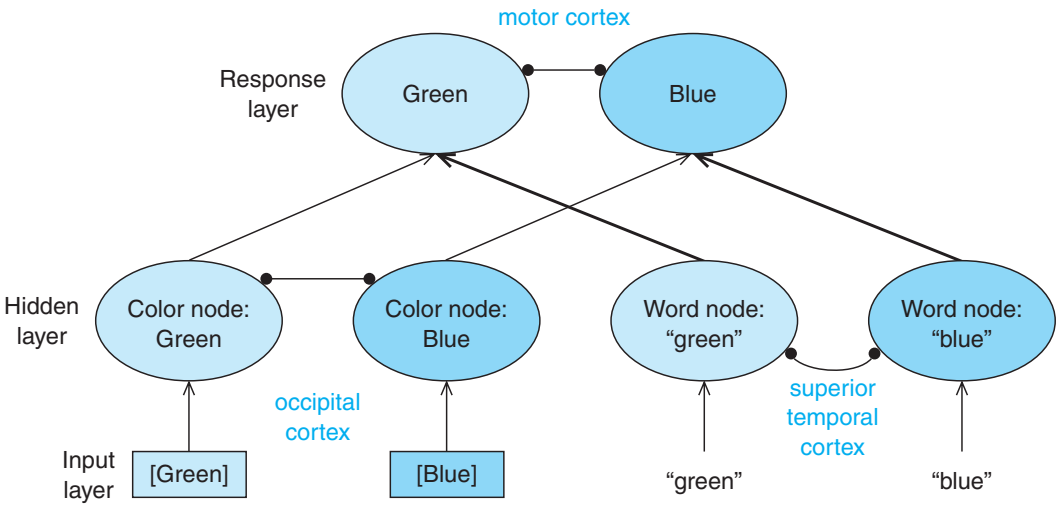


FIGURE 7–8 A three-layer neural-network model of the cognitive processing in the Stroop task

The bottom layer is the input layer, where both color and word information are encoded. From here information flows to the hidden level ("hidden" because there's no direct connection to the outside world): color information flows to the corresponding color nodes, and word information to the corresponding word nodes. The top level is the response layer: both color and word information from the hidden level flow to corresponding nodes at the response level. Presumably the connections between the word nodes at the hidden level and their corresponding response nodes are stronger than the comparable connections between the color nodes and their corresponding response nodes (as indicated by relative line thickness). The word nodes should dominate at the response level, and the participant should make many errors on incompatible trials. The neural structures that likely mediate each cognitive component are indicated. Lines with arrowheads indicate excitatory connections; lines with filled circles indicate inhibitory connections. (See text for additional features of this model.)

nodes; these associations vary in weight, or strength. To keep things simple in the figure, the relative weight of a connection is shown by the line's thickness, rather than by a number, and we have not bothered to designate the activation values for the representations—you can assume they are all equal (at the start). Connections with arrowheads are excitatory, which send activation from one node to another; connections with dark circles are inhibitory, which decrease the activation level of the recipient node. Note that within both the hidden and response layers, the connections are largely inhibitory (as in the Stroop task, where the stimulus can be only one color—"if it's blue, it can't be red"—and only one response can be made).

When input is presented during the Stroop task, both color representations and word representations are activated (see the input and hidden layers in Figure 7–8). Because the word representations in the hidden layer have stronger connections to their relevant response nodes—these connections are relatively automatic—the response node for the color word will usually be activated (*usually*, not *always*, because there's noise in the system). Thus, even normal participants should make many errors on incompatible trials. But they do not, so something is wrong with the model.

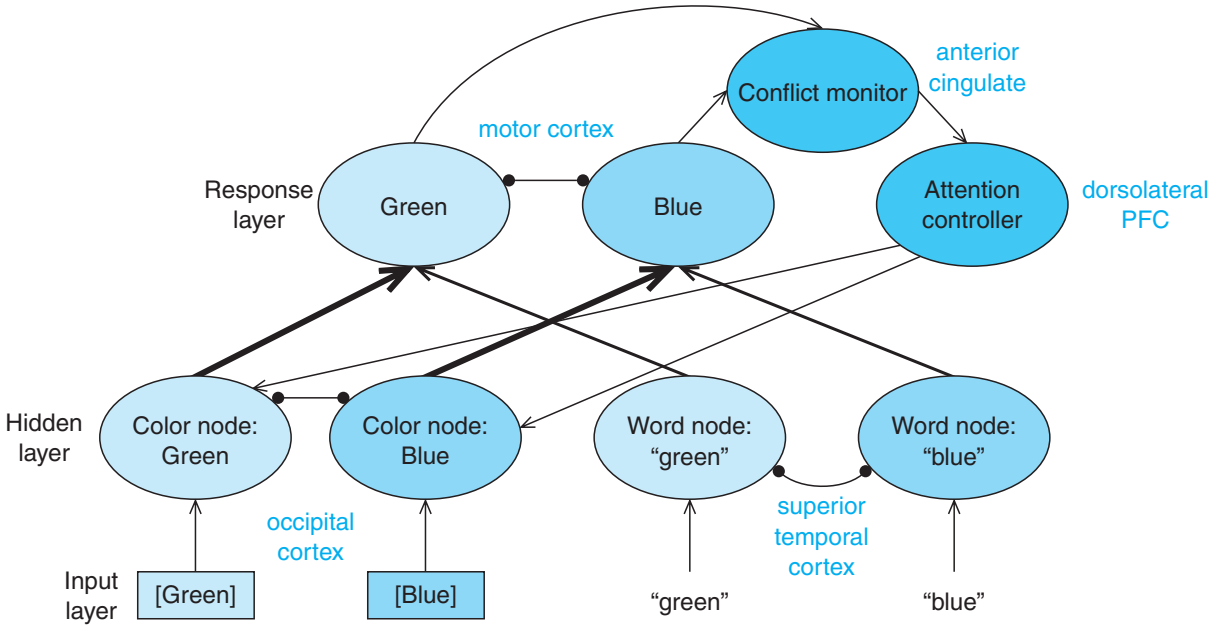


FIGURE 7–9 An amended model for the Stroop task

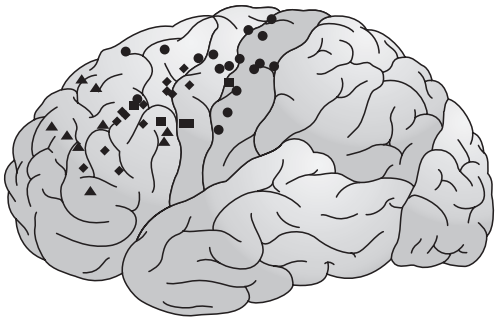
The critical additions to the model in Figure 7–8 are an *attentional controller,* which adds activation to all color nodes at the hidden level, so their connections to the corresponding nodes at the response level are now stronger than the connections between the word nodes and their corresponding response nodes; and a *conflict monitor,* which monitors the amount of conflict at the response level. The neural structures that likely mediate each cognitive component are indicated.

What's wrong is that the model does not contain an executive-attention component. This component (and another) has been added in Figure 7–9. Cohen et al. (e.g., 1996) refer to this component as an **attentional controller**. The attentional controller contains an indication of the current goal and adds activation to nodes relevant to that goal. Thus, continuing to use the Stroop task as an illustration, the attentional controller indicates the current goal—"respond on the basis of ink color"—and it adds activation to all the color nodes in the hidden layer, so that their connections to the nodes in the response layer are stronger than the well-learned (and hence strong) connections between the word nodes and their corresponding response nodes. The result is that participants now should be highly accurate even on incompatible trials, as they in fact are. But why do incompatible trials take longer than compatible ones? Because some of the activations from the word nodes are still gaining access to their corresponding response nodes; on compatible trials this activation will just add to the activation of the correct response node, but on incompatible trials the irrelevant activation will compete with the relevant activation from the color node. (Competition occurs because there are inhibitory connections between the response nodes.)

The other additional component in Figure 7–9, which ties the whole model together, is a **conflict monitor**. This component monitors the amount of conflict between the nodes at the response level, and as conflict increases, the monitor engages

executive attention. To the extent this conflict is high, the conflict monitor increases attention, via the attentional controller. (Conflict between two responses is high when they are roughly equally activated, less so when the difference in activation is greater.) So this is the overall picture: when the required response is automatic or straightforward, there is no conflict at the response level, and no need for the use of executive attention. (This is the case when participants are presented with color names printed in different ink colors and the task is simply to *read the words,* an automatic process for literate adults.) But when the required response is not automatic, measurable conflict will occur at the response level, which will be detected by the conflict monitor, which will turn on executive attention, which in turn imposes the requirements of the current goal on processing. (This is what happens when participants must name ink colors incompatible with the color name.) As for the breakdown in performance in patients with frontal damage, presumably this results from a deficit in executive attention. Thus, Figure 7–8, which lacks both a component for executive attention and a signal to engage it, provides a possible model of performance for patients with damage to the frontal lobes.

Progress has also been made in specifying the neural bases of the critical components in the neural-network model shown in Figure 7–9. Researchers have conducted many neuroimaging studies of participants performing the Stroop task and related tasks, and Jonides et al. (2002) surveyed a number of such studies to determine whether certain common regions were activated in all these tasks of executive attention. The results are shown in Figure 7–10. Each symbol represents an activation obtained in one of the studies. One significant cluster of symbols is in the anterior cingulate (which is known to be involved in monitoring processing), another is in a region that mingles with the anterior cingulate at its most ventral extent, and the third significant region is in the right-hemisphere dorsolateral PFC. This last area is



Left Lateral View

FIGURE 7–10 A summary of neuroimaging results on the Stroop task

Points on this schematic brain represent the major activations from different imaging studies on the Stroop task (represented by different symbols). The points form a large cluster that extends from the dorsolateral PFC to the anterior cingulate.

(Jonides, J., Badre, D., Curtis, C., Thompson-Schill, S. L., and Smith, E. E. (2002). Mechanisms of conflict resolution in prefrontal cortex. Adapted from *The Frontal Lobes,* edited by D. T. Stuss and R. T. Knight, copyright © 2002 by Oxford University Press. Reprinted by permission of Oxford University Press.)

known to be important for working memory and executive processes (as discussed in Chapter 6), and it is highly interconnected with the anterior cingulate.

These results fit relatively well with the theory. Presumably the anterior cingulate mediates the conflict monitor, and the dorsolateral PFC mediates executive attention. Some striking imaging evidence exists for this proposal. The evidence comes from an fMRI experiment (MacDonald et al., 2000) that involved the Stroop task and a reading task. In part 1 of each trial an instruction was presented that told the participant whether the task will be to name the ink color or to read the word. Part 2 occurred several seconds later and presented a color name printed in a particular color ink. Consider what should happen during part 1: if participants are told that a reading task is coming (and if they are fluent readers), there's no need for executive attention; in contrast, if participants are instructed that a color-naming task is coming they know that they will need attentional help (presumably they know this from past experience, possibly their experience in practice trials). When they know that they need help, they initiate executive attention. Because executive attention is mediated by the dorsolateral PFC, the images of brain activity should reveal a difference between dorsolateral PFC activity in part 1 between the two instructions. But there should be no difference in the anterior cingulate, because there's no conflict yet—the actual task, which does involve conflict, has not yet been presented. This pattern of brain activity is exactly what was found (Figure 7–11a).

Now consider what should happen in part 2, those trials when participants have to name colors in the Stroop task. On incompatible trials, there should be conflict at the response level, which should be noted by the conflict monitor, which is mediated by the anterior cingulate. So the images of brain activity for color naming during part 2 should reveal different levels of activity in the anterior cingulate for compatible versus incompatible trials. Again, the results conform with the predictions (Figure 7–11b).

Another way of viewing this model and others like it (e.g., Polk et al., 2002) is shown in Figure 7–12. As you can see, in the Stroop task and other conflict tasks, activation travels from the PFC in the front of the brain to a region in the back. This front-to-back processing is the heart of models of executive attention. In the Stroop test, activation goes from the PFC to the fusiform gyrus, in the back of the brain, where color is processed. In tasks involving conflict in motor responses, such as making a left-handed response to a right-handed stimulus, activation from the PFC travels to areas involved in motor planning—the premotor cortex behind the PFC. Control is in the front of the brain; what gets controlled is farther back.

The monitor-plus-attention model we have been describing is consistent with behavioral data from frontal-lobe patients and behavioral data and neuroimaging evidence from neurologically healthy people. It is at present the dominant theory of executive attention. Still, the model is not without its critics. One challenge comes from researchers who have argued that there is more than one kind of attention–inhibition in play in the Stroop task and related tasks (e.g., Jonides et al., 2002). According to Milham and colleagues (2001), attention can be needed either at the response level or *earlier in the processing,* and only the response level activates the anterior cingulate. These claims are supported by experiments using our old friend, the Stroop task. Milham and colleagues used two kinds of incongruent trials. In the *incongruent–eligible*

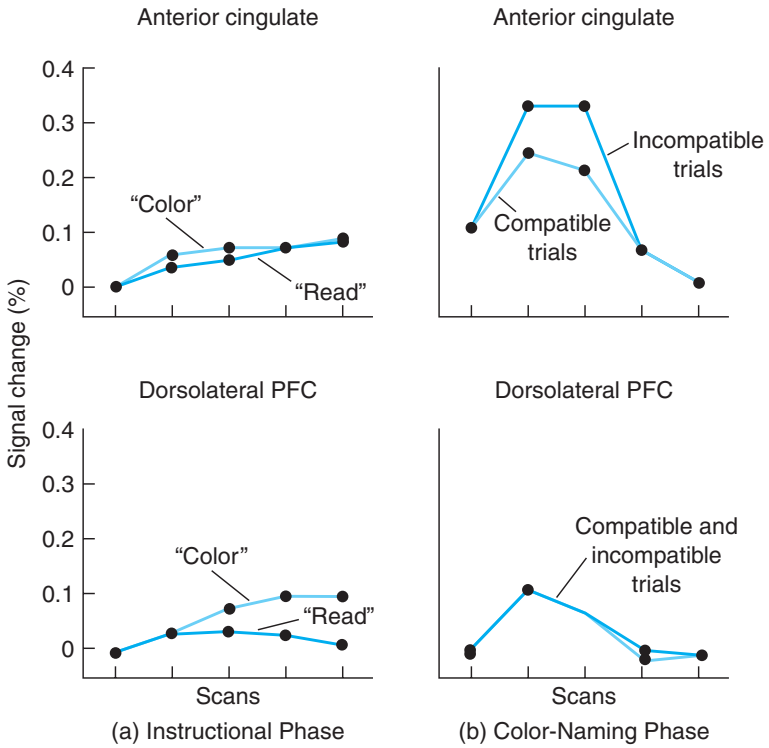


FIGURE 7–11 **Neuro-imaging evidence for a dissociation of the attentional controller and the conflict monitor**

The task includes an instructional phase, in which the participant is told whether the task will be to name the word ("Read") or the ink color ("Color"), as in the Stroop task, and a naming phase, in which the participant must sometimes name the color of the ink, which may or may not be compatible with the color word. (a) In the instructional phase, the anterior cingulate is unaffected by the nature of the upcoming task (it "cares" only about conflict); the dorsolateral PFC shows more activity when preparing for the Color task ("turn on the attentional controller") than for the Read task. (b) In the color-naming phase, the anterior cingulate shows greater activity for incompatible than for compatible trials (because there is more conflict in the former). There is no difference in activation between incompatible and compatible trials in the dorsolateral PFC. (The attentional controller presumably is used for both kinds of trials.)

(Adapted from MacDonald, A. W., Cohen, J. D., Stenger, V. A., and Carter, C. S. (2000). Dissociating the role of the dorsolateral prefrontal and anterior cingulate cortex in cognitive control. *Science,* 288, 1835–1838. Reprinted with permission.)

condition, the color names (which have to be suppressed) could also occur as ink colors, and hence were possible responses. Thus, the ink colors to be named were blue, yellow, and green, and the words used were *blue*, *yellow*, and *green*. In the *incongruent–ineligible* condition, the color names could never occur as ink colors and hence could never serve as responses. Here the ink colors to be named were, again, blue, yellow, and green, but now the words were *red*, *orange*, and *brown*. When participants were imaged by fMRI while doing this task, the dorsolateral PFC was active on both kinds of incongruent trials, but the anterior cingulate became activated only on the incongruent–eligible trials, that is, only on trials that required inhibition at the

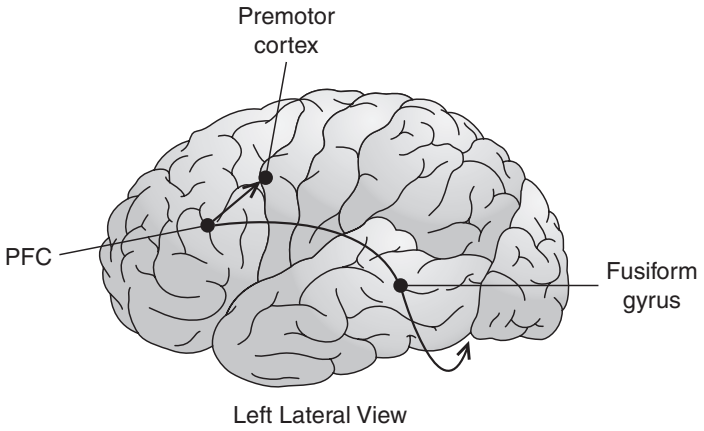


FIGURE 7–12 The front-to-back flow of brain activation when attention is required

During the Stroop task, the activation flows from the attentional centers in the PFC back to the fusiform gyrus, the area for color processing. During stimulus–response compatibility tasks ("respond right to a left-sided stimulus"), the activation flows from the attentional to the premotor cortex, behind the PFC.

response level. These results challenge the idea that the anterior cingulate is a conflict monitor, by suggesting instead that it mediates response inhibition (inhibition of a prepared or partially prepared response). In either case, however, the broad outlines of the model remain intact; it is clear that the details will continue to be determined by research just now being conducted—this is an exciting period in the history of cognitive psychology and cognitive neuroscience!

3.2. Executive Attention and Categorization

Executive attention is important in a mental process that you engage in many times a day: assigning an object to a category. That is what you're doing every time you recognize a particular creature as a dog (you've assigned the creature to the category of DOG), or when you identify a weird-looking bean-bag structure as a chair (you've assigned that object to the category of CHAIR). (Categorization was discussed at length in Chapter 4.)

Rips (1989) was interested in demonstrating that there is more to categorization than the similarity of the to-be-categorized object and the corresponding long-term memory representation. On each trial of his experiment, participants were presented with a brief description of a test object and the names of two categories; for example, the description might be "an object that is three inches in diameter" and the two categories PIZZA and QUARTER. Note that one of the categories, QUARTER, is fixed with respect to the dimension mentioned in the description—quarters are of a specific size, which is smaller than 3 inches in diameter; the other category, PIZZA, permits extensive variation on the relevant dimension. This distinction between *fixed* and *variable* categories turns out to be critical.

All participants were to decide which category better described each test object. However, different groups of participants were instructed to make their categorization

decisions in different ways. The "similarity" group was instructed to base their decision on the similarity of a test object to the categories. Because the experimenter had chosen the descriptions to be approximately equally similar to each category—the 3-inch object of the example is roughly equally similar to pizzas (round, usually larger) and to quarters (round, always smaller)—one would expect a 50–50 split between fixed QUARTER responses and variable PIZZA responses, and this was roughly what was found (Rips, 1989; Smith & Sloman, 1994). In contrast, for the "reasoning" group similarity was not enough. This group was instructed that there was always a correct answer, and to think through their decision aloud. This emphasis should have induced participants to *attend* to the size dimension of the two categories, and realize that because quarters cannot possibly be three inches in diameter (as stipulated by the U.S. Treasury), the test object was more likely to be a member of the variable category (PIZZA) than the fixed category (QUARTER). Again, these were the obtained results (Rips, 1989; Smith & Sloman, 1994), showing that the critical difference between two basic categorization strategies is whether or not executive attention plays a role.

If executive attention is indeed mediated by the PFC, then one would expect that patients with frontal damage that includes the PFC would have particular difficulties in making categorization decisions based on reasoning but not on similarity (similarity mechanisms are presumably distributed throughout the cortex). Grossman et al. (2003) confirmed this prediction. On similarity-based categorizations, frontal patients were indistinguishable from normal participants of the same age. In sharp contrast, on reasoning-based categorization frontal patients continued to select the fixed category (QUARTER) as frequently as the variable category (PIZZA) whereas the normal participants favored the variable category. Presumably the frontal patients are compromised in executive attention and hence cannot successfully apply the reasoning-based strategy (see *A Closer Look*).

Furthermore, if executive attention is indeed mediated by the PFC, then this area should be activated in normal participants when they make reasoning-based categorizations but not when they make similarity-based categorizations. Using fMRI as the means of neuroimaging, Grossman et al. (2002) have confirmed this prediction.

Here three different types of evidence about the functioning of executive attention converge: (1) behavioral studies with normal participants (PIZZA–QUARTER) have found different categorizations with similarity and reasoning instructions; (2) comparable behavioral studies with patients with frontal damage have found that only reasoning-based categorization is compromised in the patients; and (3) a neuroimaging study found that the PFC is are activated when normal participants carry out the same reasoning task, but not the similarity task. It is hard to imagine any complex cognitive process that does not involve executive attention operating on the contents of working memory.

3.3. The Role of Consciousness

We have repeatedly noted that cognitive conflict arises when the correct response must be determined by a nonautomatic process at the same time that an automatic process is competing with it. For literate adults, reading words is presumably an au-

A CLOSER LOOK
Prefrontal Damage, Reasoning, and Category Decisions

Researchers Murray Grossman, Edward E. Smith, Phyllis Koenig, Guila Glosser, Jine Rhee, and Karl Dennis sought to confirm predictions about prefrontal involvement in category decisions based on reasoning and on similarity. Their results were published in a 2003 paper titled "Categorization of Object Descriptions in Alzheimer's Disease and Frontotemporal Dementia: Limitation in Rule-Based Processing," *Cognitive, Affective, & Behavioral Neuroscience, 3*(2): 120–132.

Introduction

The investigators hypothesized that patients with damage in the prefrontal cortex would be impaired in making categorization decisions based on reasoning but not in making similarity-based decisions. This is because only reasoning-based decisions require the sort of processing mediated by the PFC, particularly, executive attention.

Method

Normal participants were compared with patients in the early stages of Alzheimer's disease (AD). Such patients are known to have atrophy in the PFC. The two groups of participants were matched on age and years of education.

The two groups of participants were tested on the two tasks used in the PIZZA–QUARTER experiments of Rips (1989) and Smith and Sloman (1994). In both tasks a trial starts with a brief description of a test object (or event), for example, "an object three inches in diameter," followed by two categories, PIZZA and QUARTER. In the similarity condition, participants were instructed to base their decisions on the similarity of the test object to the categories; in the reasoning condition, participants were told there was a correct answer and were encouraged to "think aloud," using reason in making their decisions (quarters are a fixed size, the size of pizzas is variable). If the hypothesis of the present investigators is correct, then AD patients should not differ from normal participants in the similarity condition, but should perform more poorly than normal participants in the reasoning condition (that is, they should choose the variable category less often).

Twenty-five different items were used, all having the same structure as the PIZZA–QUARTER example. Different groups of normal participants were used in the two conditions, similarity and reasoning, because memory for the response in the first condition might contaminate responses in the second condition. For the AD patients, it was possible to test the same participants in both conditions, as long as a month intervened between the conditions. (After a month's time, the AD patients had lost all memory of the first test; memory loss is the primary symptom of AD.)

Results and Discussion

The data of interest are the percentage of times each group of participants chose the variable category. For the similarity condition, the percentage choice of the variable category was 58 percent for normal participants and 59 percent for the AD patients. There was no difference between the groups when executive attention (and thus the PFC) is not involved. This finding is consistent with the hypothesis. For the reasoning condition, the percentage choice of the variable category was 78 percent for the normal participants and only 58 percent for the AD patients. Normal participants did better than AD patients when executive attention (and PFC resources) is required. This finding provides direct support for the hypothesis.

tomatic process, whereas naming ink colors is not (and hence requires attention for help); this contrast would account for the results we have seen in the Stroop test. But what exactly do terms like *automatic* and *nonautomatic* mean? The answer may partly involve consciousness.

According to most views, an **automatic process** is one that can be initiated without intention (in Stroop, you read the word whether you want to or not), that operates very rapidly (it takes about half a second to read a word), and, most important for our purposes, that can operate without *consciousness* (you don't have to attend consciously to the word to get its name). In contrast, a nonautomatic process (often called a *controlled process*) is one that requires intention (you have to want to name the print color), is relatively slow, and requires consciousness for its operation (we have to attend consciously to ink color) (Posner & Snyder, 1974; Shiffrin & Schneider, 1977).

But what, exactly, do we mean here by the term *consciousness*? Consciousness is a state that is accompanied by a certain phenomenology—an experience—and that experience presumably reflects certain types of information processing. Philosophers distinguish between different types of consciousness (e.g., Block et al., 1997). At a low level is *awareness consciousness,* a state in which you aware of the stimuli and events presented to you. At a higher level is a kind of *introspective consciousness,* in which you are aware not only of external stimuli but also of internal representations and processes. The distinction is important in dealing with questions such as whether certain kinds of brain damage differentially affect different types of consciousness, and whether nonhuman species may have awareness consciousness but not introspective consciousness. Clearly the kind of consciousness that we have been talking about is of the introspective type, because we have considered models in which we monitor for internal conflict.

There is consensus that the information processing resources that give rise to consciousness are limited (as William James suggested more than a hundred years ago). Consequently, we can be conscious of only a limited number of things at a time. Indeed, some have placed this limit at one (McElree & Dosher, 1989). If limited resources are posited, the processing underlying consciousness seems a lot like attention, and indeed the two concepts are tightly intertwined. It may be that whenever we attend to some stimulus or mental representation, we are conscious of it (this has been assumed throughout much of this book. Just what the function of the phenomenology of consciousness is remains controversial.

Whereas nonautomatic processes seem to require the resources that give rise to consciousness, automatic processes do not. We are generally not aware of the processing involved in reading a word or reaching for a cup. In many cases, what once required conscious processing no longer does so after extensive practice. Sports provide some excellent examples. Beginning tennis players may be very conscious of the components of their strokes, reminding themselves to get to the destination of the ball first and then bring their racquet all the way back, but seasoned players perform these essential actions unconsciously.

What do we know about the neural basis of consciousness? One suggestion is that in conflict situations such as Stroop, the anterior cingulate comes on line only when the conflict is conscious (Jonides et al., 2002). A broader hypothesis has been offered by no less than Francis Crick (the co-discoverer of the structure of DNA), working

with Christof Koch. On the basis of a number of cognitive-neuroscience results, Crick and Koch (1995) speculated that information cannot become conscious until it reaches the frontal lobe. Only time will tell whether the suggestion has merit.

Comprehension Check:

1. How do patients with frontal damage differ from normal participants on the Stroop task?
2. In the neural network model of the Stroop task, what two components come into play on incompatible trials?

4. SWITCHING ATTENTION

There you are in the hot kitchen, the phone ringing, the water coming to a boil, a favorite song coming over the speakers. You keep going in this crowded environment by executive attention, focusing on one or another aspect of what's going on as needed. How do you get there—how do you get from focus on phone to focus on pasta? To control internal processing, we not only have to be able to attend to some representations and processes, but must also be able to *switch* our attention from one representation or process to another. In **switching attention**, the focus of attention is moved from one entity to another, so it becomes possible for you to get dinner on the table.

4.1. The Costs of Switching

Switching attention has often been studied by having participants do one task on the first trial, another task on the next trial, then return to the first task on the third trial, the second task on the fourth trial, and so on until a set of trials is completed. For example, all trials may contain a digit and a letter, and on trial 1 the participant has to attend to the digit and decide as quickly as possible whether it is above or below 5, then on trial 2 the participant must attend to the letter and decide whether it is a vowel or a consonant, then back to digit decisions, then back to letter decisions, and so on (e.g., Rogers & Monsell, 1995). This alternation of tasks is compared to the case in which the participant performs the same task throughout an entire set of trials. The participant makes only "above-below 5" decisions for an entire set of trials, and then vowel–consonant decisions for an entire set. Sets with alternating tasks are called *alternating blocks;* sets with only one task are called *pure blocks*. To see whether the act of switching takes time, the time for the average of the pure blocks is subtracted from the time for the alternating blocks. The general finding, and it has been obtained many times, is that participants require more time to respond on alternating blocks than on pure blocks. This time difference, usually on the order of 100 to 300 milliseconds, is often referred to as the **switching cost**.

But wait a minute—the alternation condition does not seem to have much to do with what happens in life. You don't alternate between cooking and talking on the

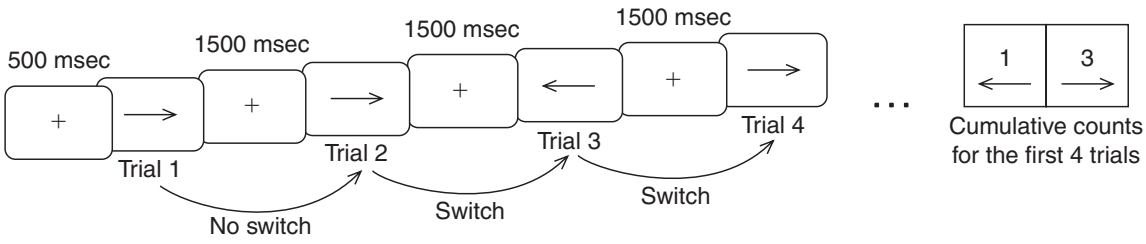


FIGURE 7–13 A sequence of trials in an attention-switching task

Participants must keep cumulative counts of left- and right-pointing arrows; on each trial, they push a button to indicate that they have updated the appropriate count. Between trials a fixation point (a plus sign) appears on the screen for 1500 milliseconds. In this example, there is no switch of counts between trials 1 and 2, but there are switches between trials 2 and 3 and between trials 3 and 4.

(Hernandez-Garcia, L., Wager, T. D., and Jonides, J. (2003). Functional brain imaging. In J. Wixted and H. Pashler (eds.), *Stevens Handbook of Experimental Psychology,* Third Edition, Vol. 4: Methodology in Experimental Psychology, pp. 175–221. New York: Wiley & Sons, Inc. Reprinted with permission.)

phone on some kind of schedule—and what if a third need screaming for your attention arises? What happens in life is that you tend to each need as required; you do each task as it is called for, and it is unpredictable which task is required moment to moment. Are there studies that capture this kind of ad hoc switching? Yes.

For example, an experiment by Garavan (1998) fits the bill, and a variant of it is illustrated in Figure 7–13. On each trial participants see, for instance, either a left-pointing arrow or a right-pointing arrow, and their job is to keep cumulative counts of the appearance of each type of arrow. Presumably, the two cumulative counts are held in a state of readiness in working memory. Once the stimulus is presented and the appropriate count updated, the participant pushes a button to bring on the next stimulus. As we will see, the time taken to press the button can be used to assess switching cost. At the end of a block of trials (about 15 to 20), the participant is tested on the two final counts; accuracy is typically high. High accuracy indicates that the switching process works—but at what cost?

When successive trials involve the same stimulus (for example, a right-pointing arrow followed by a right-pointing arrow), participants have to update the same count that they have just worked on. But when on other successive trials the stimulus changes (i.e., right-pointing arrow is followed by left-pointing arrow), participants have to switch from one count to the other to make the update. The time to press the button to bring on the next stimulus should be greater—and it is—when a switch in count is called for than when it is not; this difference in time is the switching cost. And the cost is substantial—on the order of 500 to 600 milliseconds. This difference is so large that it cannot be attributed to some kind of perceptual priming that might occur when identical stimuli are seen in succession. True, seeing the stimulus once might "grease the wheels" for seeing it again and thus contribute to participants' greater speed when the same stimuli appeared in succession (a kind of implicit memory); however, such visual priming effects are much smaller than the differential found here. Thus, switching costs are evident even in tasks that have the same unpredictable structure as natural situations.

4.2. A Framework for Understanding Task Switching

Strong evidence that switching attention is a metaprocess—a process that coordinates other processes—that also provides an information-processing framework for understanding task switching comes from a set of studies by Rubenstein et al. (2001). Participants were required to shift attention between different attributes of multidimensional stimuli. The task, based on the idea of alternation, was modeled after the Wisconsin Card Sort task. Designs on four target cards vary in the number, shape, color, and size of the pictured objects. Participants must sort each test card in a deck into one of four piles according to a particular attribute, and they always know what that attribute is. In the alternation condition, participants sort on the basis of one attribute, for instance, shape, on the first trial—that is, for the first card; then on the basis of a different attribute, for instance, number, on the second trial; switch back to shape on the third trial; switch back to number on the fourth trial; and so on for an entire block of trials. In other conditions, the participants sort on the basis of the same attribute for the entire block (that is, in pure blocks). The time to sort a card in the alternation condition takes longer than the comparable time in the various pure-block conditions. Again, switching attention takes time.

The same investigators provide a sketch of a simple information-processing model of what is going on in this and other switching tasks. The model is presented in Figure 7–14. Note first that there are two different levels of processing, task processing and executive processing, and the latter can influence the former (hence, again, the notion that executive processes are metaprocesses). The task-processing level requires the following sequence of processes: identify the value of the stimulus on the critical attribute ("It's the shape of a square!"), select the appropriate response

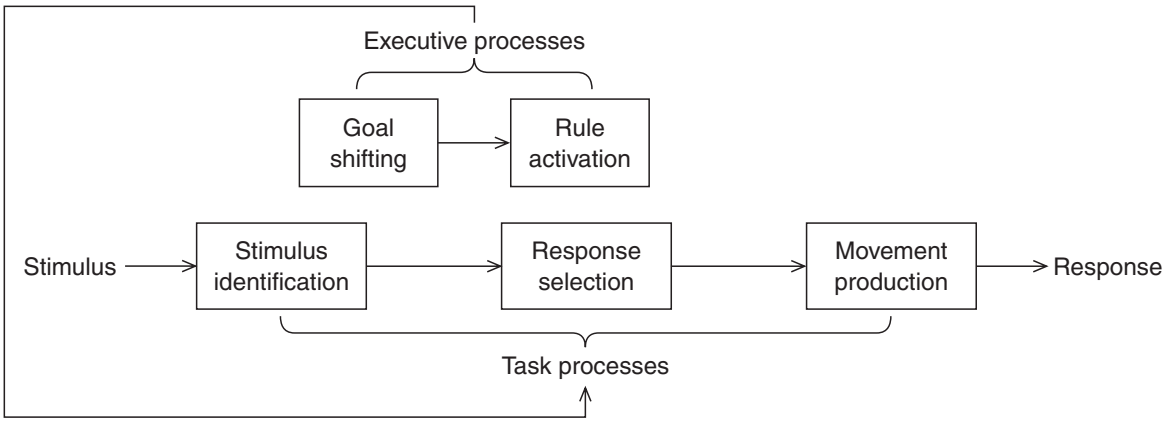


FIGURE 7–14 An information processing model for task switching

The model has two levels, task processing and executive processing, which differ in the kinds of operations they perform. Of particular importance, the executive processes include goal shifting (for example, "now sort according to number") and rule activation (for example, "selectively attend to numerosity").

Adapted from Rubinstein, J. S., Meyer, D. E., and Evans, J. E. (2001). Executive control of cognitive processes in task switching. *Journal of Experimental Psychology: Human Perception & Performance,* 27(4), Fig. 1, p. 770.

("place this card in the square pile"), and then actually make the needed movement. The executive-processing level requires different processes. First, set the goal for the trial ("sort according to shape"), then activate the rules needed to implement the goal ("attend to shape"). In the alternation, or switching, condition, a new goal must be set on every trial ("sort by shape," "sort by number," "sort by shape," . . .), whereas in the pure conditions the goal need not be changed during a block of trials. This is one reason why switching attention takes time. Further, in the switching condition, the activated rules change from trial to trial, whereas in the pure conditions the rules stay the same throughout the entire block of trials. Changing rules takes time—this is the second reason why switching takes time.

Perhaps the best evidence for the model in Figure 7–14 is that Rubenstein et al. (2001) were able to show a double dissociation between the task-processing and executive-processing levels. In this double dissociation, a given variable affects one level of processing but not the other, whereas another variable shows the opposite pattern. The fact that one variable affects task processing but not executive processing implies that there must be some mechanism in the former that is not present in the latter, whereas the fact that another variable affects executive processing but not task processing implies that there must be some mechanism in the former that is not present in the latter. Hence, a double dissociation is strong evidence that two different mechanisms are involved.

Specifically, Rubenstein et al. (2001) used two arithmetic tasks—addition and subtraction—and participants either alternated between the two tasks or did just one for an entire block of trials. To influence the executive level, the researchers manipulated the ease of changing goals by either including the operator sign (+ or −) with the problem or not. Including the operator sign relieved the participants of having to remember which task they should be performing, and thereby should have speeded the changing of goals. This in turn should decrease the switching cost (the time difference between performance in alternating and in pure blocks), because this cost supposedly arises in part from goal changing. This is exactly what the researchers found. Furthermore, in the pure conditions, inclusion of the operator sign had no effect; so this variable—presence or absence of the operator sign—had no effect on the task-processing level, but it did affect the executive-processing level. This is half the double dissociation.

To complete the double dissociation, the researchers manipulated a factor that, in theory, should have an effect on the task-processing level but not on the executive-processing level. That variable was simply the discriminability of the numbers—they were either easy or difficult to see. As expected, low discriminability increased response times in all conditions but had no effect on switching time (because it had no effect on goal switching or rule changing). This is the other half of the double dissociation.

The framework depicted in Figure 7–14 is also consistent with another result in task switching: switching costs become greater as the two tasks become more similar. Suppose in one case that participants have to alternate between addition and subtraction, whereas in another they have to switch between addition and generating an antonym to a given word. Suppose further that the antonym task takes the same amount of time as the subtraction task, so the difficulty level in both instances is the same and any differences in switching costs therefore cannot be attributed to

different demands of the individual tasks. Obviously, the two arithmetic tasks are more similar than are the addition and antonym tasks. Results in a number of studies show that the switching costs are higher in the first case than the second (e.g., Allport et al., 1994; Spector & Biederman, 1976). How does the model account for this? The more similar the two tasks, the more similar the relevant rules and the greater the opportunity for confusion in activating the rules; and the more confusion in these metaprocesses, the longer it takes to accomplish the switch. Thus, when trying to activate the rules for subtraction, you might have some difficulty in keeping them separate from the rules for addition, but no such difficulty should arise when activating the "rules" for coming up with an antonym.

Thus, the model depicted in Figure 7–14 has some behavioral support. But it does not look anything like the model for executive attention presented in Figures 7–8 and 7–9, in that the current model is a sketch of an information-processing model, whereas the models in Figures 7–8 and 7–9 are neural-network models that include detailed mechanisms.

4.3. The Neural-Switcher Hypothesis

Behavioral results, as we have seen, support the idea that additional mechanisms are brought into play when we must switch attention. Is there any neurological evidence for this? Yes, and much of it comes from neuroimaging studies. To start, participants have performed the attribute-shifting task employed by Rubenstein et al. (2001)—sort by shape, sort by number, sort by shape, and so on—while having their brains imaged by PET. When the patterns of activation for the pure conditions were subtracted from those for the alternation condition, the result—known as a *subtraction image*—showed a very substantial activation in the PFC, particularly dorsolateral PFC, as well as clear activation in the parietal cortex (Meyer et al., 1998). The attribute-shifting task is a close cousin of the Wisconsin Card Sort task, which is used to detect frontal damage—and no wonder, given that the card sort involves switching, that the dorsolateral PFC may underlie switching, and that this area is often compromised in frontal damage.

But these results also raise a number of new issues about task switching and executive processes in general. First, the neuroimaging results imply that regions of the parietal cortex are involved, suggesting that the neural mechanisms mediating switching are not confined to the frontal cortex. This is the first evidence we encounter against the strong frontal-executive hypothesis—that executive processes are mediated only by the frontal cortex. More such evidence will be presented later.

A second general issue raised by the neuroimaging results concerns the degree to which neural regions are dedicated to specific cognitive processes. One region associated with switching—dorsolateral PFC—is also involved in executive attention. How is it possible for one region to have two functions? Perhaps it does not—the problem may be methodological. The spatial resolution of PET is only about 10 millimeters, which means that it cannot discriminate between activations from two different brain regions—one doing attention and one doing switching—that are within 10 millimeters of each other. But this possibility is doubtful, given that other neuroimaging studies of

switching that used fMRI, which has better spatial resolution than PET, also found that switching per se is associated with activations in the dorsolateral PFC and the anterior cingulate, both structures that have been activated in studies of executive attention. Another possibility is that the same neural mechanism mediates both executive attention and attention switching, but more of that mechanism's resources are typically needed when switching attention than when just attending. This possibility raises an important question about the neural bases of attention switching: Is there any evidence that there are neural mechanisms *dedicated solely* to switching?

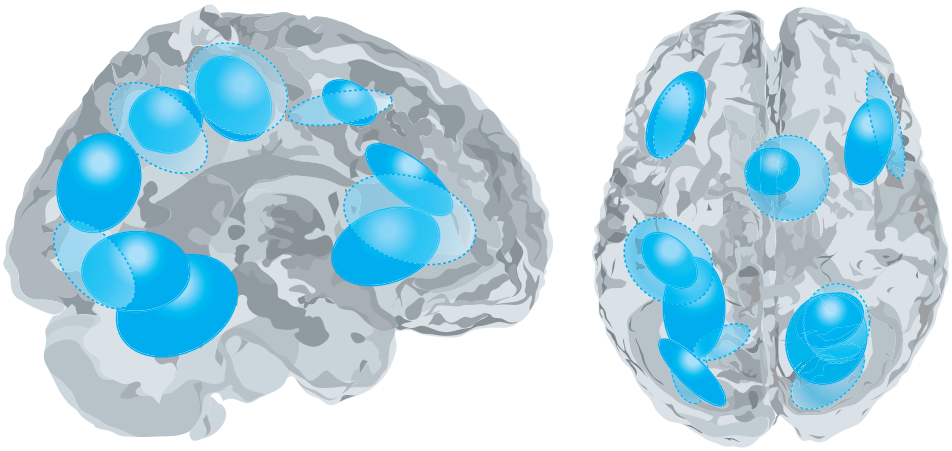
An experiment by Sylvester et al. (2003) offers direct evidence on this issue of specificity. While being imaged by fMRI, participants worked on two different kinds of tasks: the cumulative-counts task described earlier ("How many left-pointing arrows?" and "How many right-pointing arrows?"), which is a good example of task switching, and a stimulus–response compatibility task, such as left-handed stimuli–right-handed responses and vice versa, which presumably taps executive attention and inhibition. In the count task, Sylvester et al. obtained the subtraction image—the difference in activations—for switch minus nonswitch conditions, which provided an indication of the neural location of the switching regions. In the stimulus–response compatibility task, the researchers obtained the subtraction image for the incompatible minus the compatible trials, which provided an indication of executive attention areas. Now the crux of the question: comparison of the two subtraction images. Do they show any substantial differences? Yes, they do. Areas distinct to switching include regions in the inferior parietal lobe and the extrastriatal visual cortex, whereas areas distinct to executive attention include two frontal areas, one in the anterior PFC and the other in the premotor cortex. (Are you wondering why the dorsolateral PFC did not show up? Activation in this area was cancelled out in the critical comparison in this experiment because PFC was activated roughly equally in both executive attention and switching executive attention). Because distinct neural processes suggest distinct cognitive processes, we have evidence that the process of switching executive attention is distinct from that of engaging executive attention. This work also provides further evidence for the role of the parietal lobes in attention switching, and further evidence against the strongest version of the frontal-executive hypothesis.

4.4. What Gets Switched?

You may have noticed that in all this discussion of switching we have been rather casual about what exactly gets switched. In addition–subtraction studies there is a switch in the actual task the participant has to carry out. In the cumulative-counts task, participants switch between different mental representations in working memory, but there is no real switch in task. In some tasks participants switch between different attended attributes of the same stimulus (sort by number–sort by color–sort by number); again, there is no real change in task. That is a total of three kinds of switches—switch of task, of representation, and of attended attribute—and there are other kinds of switches as well. The obvious question: does it make a difference what exactly is switched?

There is some relevant neural evidence on this point. The evidence is in the form of a *meta-analysis* (i.e., an analysis in which one pools the results of numerous studies, and tests statistically whether the studies are showing the same effects) of neuroimaging studies of switching (Wager et al., 2003). To conduct the meta-analysis, these investigators first put together on one schematic brain the peaks of the activations from switching studies that involved either attended attributes or tasks. (There were not enough studies on switching working-memory representations to include in the analysis.) Then they applied a *clustering algorithm*—a computer program that determines whether the peaks fall into clusters rather than being evenly distributed throughout the brain. In particular, the investigators wanted to determine: (1) whether the peaks for switching attributes fell into a few separate clusters; (2) similarly, whether the peaks for switching tasks fell into a few clusters; and (3) the extent to which these two sets of clusters overlap. The results are presented in Figure 7–15.

Figure 7–15 shows the brain as if it were glass. In Figure 7–15a, we are looking *through* the right lateral cortex. Thus, we can see *all* the clusters (but since we have essentially collapsed the brain horizontally, we cannot tell whether a cluster is in the left or the right hemisphere). What is abundantly clear in the figure is the substantial overlap between clusters for switching tasks and clusters for switching attributes. These results imply two conclusions: switching tasks and attributes seem to involve the same neural mechanisms, and many of the relevant neural mechanisms are located



(a) (b)

FIGURE 7–15 A meta-analysis of switching

Clusters of activations from studies that involved either switching attributes or switching tasks are shown on (and in) a "glass brain." (a) In this view, it is as if you are looking through the brain from the right side. As is evident, almost all the clusters for switching attributes (shown in dark blue, with solid outlines) overlap with the clusters for switching tasks (shown in light blue, with dotted outlines). This means that the regions activated when switching attributes are roughly the same as those activated when switching tasks—that is, there may only be one neural switcher. (b) In this view of the clusters, it is as if you are looking through the brain from top to bottom. The conclusions remain the same.

in parietal cortex, which again argues against the frontal-executive hypothesis. Figure 7–15b provides the same data from a different view. Now it is as if we are looking from the top, down through the brain, so now we can distinguish clusters on the left from those on the right. Our two conclusions remain unchallenged.

These results are relatively new, and they need to be backed up by at least two different kinds of studies. First, we need neuroimaging studies that compare two or more switching types *in the same participants*. The meta-analysis does not do this, because its input—activation peaks—was drawn from different experiments. Second, we need behavioral experiments that seek to determine whether or not switching in different ways is affected by different factors. At least one behavioral study indicates that there may be little difference in switching between attributes and objects (Waqer, et al., 2006). As usual, we want converging evidence.

Comprehension Check:

1. How can a switching cost be demonstrated?
2. According to the model of attention switching discussed, what are the underlying causes of a switching cost?

5. INHIBITION OF RESPONSE

How can we tell the difference between attending to something and ignoring everything else—in other words, the difference between focusing on one thing and inhibiting another? In the Stroop task, it is difficult to determine whether the basic phenomenon—the slowing on incompatible trials where color name and ink color conflict—is due to heightened activation of the ink color or to inhibition of word names, or both. Ditto for many other executive-attention tasks. But there is one case—*response inhibition*—in which inhibition, rather than attention, clearly is the key factor. **Response inhibition** is the suppression of a partially prepared response.

Distracted by the phone call, you reach to move the pot of boiling water off the electric burner and remember only in the nick of time that you haven't picked up a potholder—you have to inhibit your reaching response, whether it has only been programmed or in fact has been initiated. Or, listening on the phone to your slightly pushy favor-seeking friend, you are getting annoyed and are about to say something that will be hard to unsay. Again, you need to inhibit a partially prepared response. Though response inhibition is only one kind of inhibition, it is an important kind that occurs frequently in everyday life.

5.1. Representative Cases of Response Inhibition

A number of experimental tasks have been designed to study response inhibition and its neural underpinnings. One is the go/no-go task, a classic test that has been widely used to assess frontal-lobe functioning. Participants are presented with a sequence of

stimuli, say, letters, and instructed to push a button at the appearance of every letter (a "go" response) *except* X ("no-go"). As long as X occurs relatively infrequently, when it does appear the task clearly requires the participant to inhibit a tendency to press the button. As the number of consecutive go responses increases, the more likely the participant will be to respond in error when an X finally shows up (Casey et al., 1997). Presumably, the longer the sequence of go trials, or the higher the probability of a go response, the more difficult it is for a participant to start an inhibitory response that will overturn the processing that underlies the go trials.

A number of fMRI studies of participants doing this task have been conducted, and the results are of considerable interest: they suggest that response inhibition is a separate executive process, distinct from those considered thus far. The critical contrast is between the regions activated on no-go trials (when response inhibition is required) and on go trials (when no inhibition is required). As frequently occurs in executive-processing tasks, our old friend the dorsolateral PFC is activated. But other brain areas get into the act as well. One such area is the anterior cingulate. Although some researchers have argued that the anterior cingulate plays a role in tasks requiring executive attention, others have provided suggestive evidence that the anterior cingulate is active in these tasks only when there is a need for inhibition at the response level (consider the distinction between eligible and ineligible responses, discussed on page 308). Perhaps most interesting, in response inhibition an additional PFC region is sometimes activated, the orbitofrontal cortex (which is below the dorsolateral PFC). Furthermore, activation in this other region is correlated with performance in the task: participants who show more activation in the orbitofrontal region produce fewer errors on the no-go trials of the task.

Studies with nonhuman primates provide evidence for orbitofrontal cortex involvement in inhibition (e.g., Iverson & Mishkin, 1970; Sakuri & Sugimoto, 1985). In these studies, lesions in the PFC, particularly the orbitofrontal cortex, have been shown to produce deficits in tasks that require the inhibition of strong response tendencies. Similarly, studies with human patients who have damage in this critical region also show that the patients are impaired on tasks requiring the inhibition of responses or response tendencies (Malloy et al., 1993).

Another task (performed by human participants) that relies on response inhibition is the stop-signal task developed by Logan (1983). In a typical version of this task, participants have to reply quickly to questions concerning category membership ("Is a pomegranate a fruit?") or rhymes ("Does *sleigh* rhyme with *play*?"). On some trials, a tone is sounded—the *stop signal*—which directs participants to stop their processing on that trial and not answer the question. The critical determinant of performance in these tasks is the *stop-signal delay,* that is, the length of time between question and stop signal. The longer this delay, the more processing the participant has completed, and the more likely it is that the response tendency cannot be aborted—and therefore the more likely it is that the participant will commit an error by answering the question despite the stop signal.

But how do we know that the inhibition observed is truly an inhibition of response, rather than an inhibition of some earlier process? Logan (1983) has some decisive evidence on this point. After the stop-signal experiment just described was completed,

Logan gave the participants a surprise memory test on the critical words in the test questions. If the inhibition engendered by the stop signal had affected earlier processes, then memory for the critical words should have been poorer on trials that included a stop signal than on trials that did not. In fact, there was no difference in memory for the two kinds of trials, which indicates that inhibition affected response processes after earlier processing was completed. In subsequent studies (de Jong et al., 1995), **event-related potentials (ERPs)** (electrical activity in the brain linked to a particular "event," that is, a particular stimulus or response) were used along with electromyograms (measures of electrical activity in motor systems) and behavioral measures to show that the inhibition of response could occur at any point in the preparation and execution of response. The ERP measures, which offer some rough information about brain localization, were consistent with a frontal localization of response inhibition.

Response inhibition is vitally important in normal life. If you said everything that came to mind, or performed every action that you thought of, you'd probably soon end up friendless or worse. And a number of psychiatric disorders appear to be marked by a lack of response inhibition: witness the bizarre speech and behaviors that often appear in schizophrenia, or the blatant lack of response inhibition in some obsessive-compulsive disorders, in which patients repeat nonfunctional responses again and again. Or consider the personality trait of being unable to delay gratification, which in adulthood is often a major handicap in dealing with real-life situations, and which may heavily involve a failure of response inhibition. A recent study shows that this trait, as indexed by tests performed during childhood, is associated with poorer performance on the go/no-go test, indexed in adulthood (Eigsti et al., 2006).

5.2. Development of Response Inhibition

"Kids say the darndest things"—possibly because impulsivity, and a lack of response inhibition, may be most widespread in children. How does it come about that at some point we know (pretty much) when to keep our mouths shut?

A substantial amount of behavioral and neural research has been conducted on the development of inhibitory processes. A good deal of this research is inspired by the belief that inhibition, particularly response inhibition, is mediated by the PFC, and by the fact that the PFC undergoes one of the longest periods of development of any brain region, taking almost two decades to reach full maturity in humans (Diamond, 2002). Thus we can expect young children to have great difficulty inhibiting their responses even in simple cases, and to progress systematically in their ability to inhibit responses as they grow up. (Because the PFC clearly seems to be involved in executive attention, and in at least some cases of task switching, we would expect similar developmental trajectories for these executive processes as well.)

One of the simplest and most widely used tasks with infants is the A-not-B task, which was introduced by Jean Piaget in 1954. Infants watch as a desired object is first hidden in one of two places that differ only in spatial location. Then follows a delay of a few seconds, after which the infants are induced to find the hidden object and are rewarded when they do. If the object is hidden in the same place on the first few trials, infants have no problem reaching for that same location. But when the

desired object is switched to the other position, infants (younger than about 1 year old) still reach for the location rewarded earlier, even though they have seen the object placed elsewhere. It is as if infants cannot inhibit the previously rewarded response and select the new correct one (see, e.g., Diamond, 1985).

An alternative interpretation of these results is that the infants lack a sufficiently developed working memory to maintain the location of the desired object. Although this may be part of the story, it cannot be all, because in some trials in these experiments, when during the test phase the infant *looks at the correct location,* he or she *persists in reaching for the out-of-date location*. The infant is essentially attending to the correct choice, so this is not a problem in either attention or memory, but is reaching for the wrong place, which seems like a striking failure of response inhibition.

Children improve on the A-not-B task by the end of the first year of life, and by the time they are 3 to 5 years old they show some competency in tasks such as go/no-go. (By the time they are 7 to 12, their neural patterns of activation in go/no-go are almost identical to those of adults, although they are still not at adult levels of behavioral performance; Casey et al., 1997). Another task on which children show rapid improvement during the period of 3 to 5 years is the tapping task (Luria, 1966). On each trial, the experimenter taps either once or twice, and participants have to respond in reverse, tapping once if the experimenter taps twice, and twice if the experimenter taps once. On the face of it, the task appears to involve response inhibition (although it is awfully close to the executive-attention compatibility task discussed on pages 301–302). Neuroimaging studies with adults show that performance on the tapping task is accompanied by activation of the dorsolateral PFC (Brass et al., 2001), and it has long been known that adults with lesions in the PFC do poorly on such a task (Luria, 1966).

There is much more to the development of response inhibition (a useful starting point is Diamond, 2002), but enough has been said to make the major points response inhibition is a distinct executive process, and there is a striking correspondence between the development of response inhibition and the maturation of the PFC. The period of marked growth of the length of dendritic branches of PFC neurons—at about 7 to 12 months—exactly mirrors the period when infants first show improvement on the A-not-B task. A comparable correspondence is seen between improved performance on tasks such as go/no-go or tapping and neuronal developments in PFC. The density of neurons in dorsolateral PFC is highest at birth and declines with age, as if a pruning process (in which ineffective connections are removed) were taking place. At age 2, the density of PFC neurons is 55 percent greater than the adult number, but by age 7 it is only 10 percent above the adult number (Huttenlocher, 1990). And by age 7, children's patterns of results on tasks such as the go/no-go start to look more like those of adults. Although these correspondences do not prove that the PFC underlies response inhibition, they are certainly compatible with that hypothesis.

Comprehension Check:

1. What evidence indicates that response inhibition is a distinct executive process?
2. Why is response inhibition so important in daily life?

6. SEQUENCING

Planning: getting the pasta going before heating the fudge sauce for dessert; rearranging your schedule to accommodate a friend's request; making that schedule in the first place—all these activities require the ability to sequence operations or events to accomplish a goal. The coordination of processes necessary for planning suggests that an executive process—sequencing—is involved.

6.1. Mechanisms for Sequencing

By **sequencing** we mean, in part, coding information about the order of events in working memory. You can't form a plan to accomplish a goal without coding the order of actions or events involved. Dr. P.'s inability to execute a sequence of actions was among his most striking deficits. So a fundamental question is, what mechanisms do we use to code the temporal order of a sequence of events?

To answer this question, we first need to show that coding the order of an item requires different mechanisms than coding the identity of that item. A number of behavioral experiments suggest that it does. In one pair of studies (Sternberg, 1966, 1967), participants were tested on two related tasks, one requiring the storage in working memory only of item identity (Figure 7–16a), the other requiring the storage of order information as well (Figure 7–16b). In the item identity task, participants were presented with a series of items to remember followed by a probe item, and their task was to decide whether the probe occurred in the memory set, in any position; for this task only item information had to be stored in working memory. In the order task, participants were presented with a series of items, followed by a probe item from the series; here the task was to produce the item in the input sequence following the probe item. (For example, given the series A T G M and a probe item t, the response should be "g.") Clearly, participants had to store item and order information to accomplish this task.

In both the order and item tasks the number of items in the memory set is varied, and in both cases the time to respond to the probe increases with this variable. The data are plotted in Figure 7–16c. Look at the slopes of the lines relating response time to the size of the memory set: this relation tells us how long it takes to process each additional item (as described in Chapter 6). The graphs show striking differences between the two tasks. The slope for the order task is much steeper than the slope for the item task. The most straightforward conclusion is that storing and retrieving order information involves additional processes than are required for storing and retrieving item information. Some of this difference could be due to the fact that the first task involves recognition whereas the second requires recall. But other data, as we will see, support the idea that item and order information are stored and processed differently.

Why think that coding order information—that is, sequencing—is an executive process? For one thing, it certainly is a metaprocess, because virtually any kind of items or events can be coded for order information. And it has long been known that patients with frontal-lobe damage are deficient in coding order information compared to item information. In a study by Corsi (cited in Milner, 1971) frontal-damage

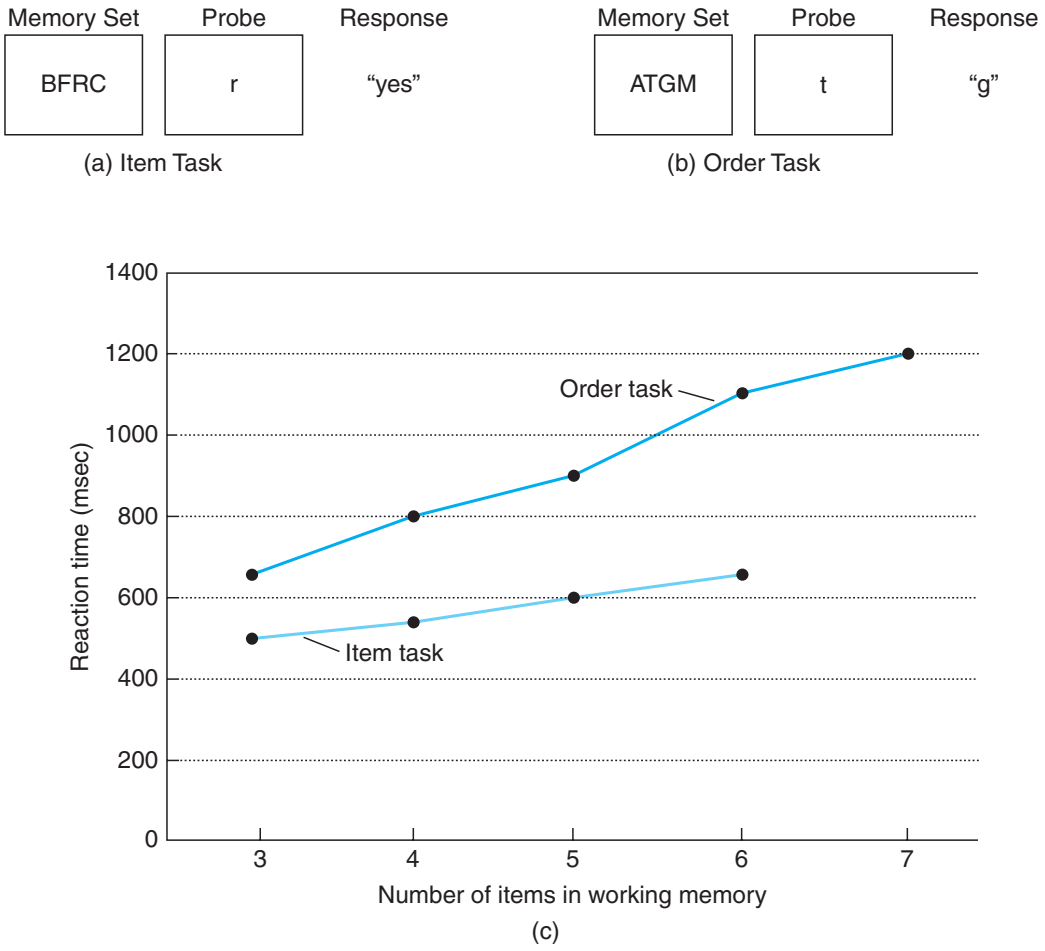


FIGURE 7–16 **Retrieving item versus order information**

(a) This task involves only item identity information: participants must decide only whether the probe occurred in the memory set. (b) This task requires the storage and retrieval of order information as well as item identity information. Now participants must report the item that *followed* the probe item in the memory set. In both tasks the probe is in a different case from the memory set to prevent participants from using a visual matching strategy. (c) The data plotted: these two tasks lead to sharp differences in the way that information is retrieved from working memory.

patients and parietal-damage patients were shown a series of pairs of items; occasionally the two items in a pair would appear with a question mark between them. The patient's task was to decide which of the two items had appeared more recently. When only one of the items had actually been presented previously, this was a test of item recognition; when both items had been previously presented, this was a test of order memory as well as item memory. The results showed a striking double dissociation. The frontal-damage patients were impaired on order information, but not on item memory, whereas the parietal-damage patients showed the opposite pattern—impairment on item memory but not order memory. These findings have been strengthened and extended in subsequent studies (B. Milner et al., 1991).

How might order information be represented? Three well-known possibilities are worth considering. To be specific, let's discuss these mechanisms in the context of an experiment in which participants are shown a short series of items to remember (for example, J G X R L B) followed by a pair of probe letters, both of which were in the memory set (for example, G L). The participant's task is to decide whether the probe letters are in the same order as they were in the memory set (they need not be adjacent; so the answer in the example is yes). One possible order mechanism is to form directed associations between every pair of successive items—J precedes G precedes X, and so on (e.g., Burgess & Hitch, 1999). With this mechanism, the farther apart two items are in the memory list, the longer it should take to determine that they are correctly ordered because more associations have to be traversed (G L should take longer than G R).

A second possible order mechanism is that we attach "order tags" to the items: J is tagged as the first item, G as the second item, and so on. With this way of representing order information, there is no reason for the time to decide on the order of the probe items to depend on the distance between the two items in the input list.

A third possibility is that you code order information on the basis of familiarity: perhaps when asked to decide whether G preceded L, the participant might simply check the familiarity of the two items; presumably the representation that is less familiar has decayed more than the other, is less strong, and hence likely occurred earlier (e.g., Cavanaugh, 1976). (In this way of coding order information is represented continuously, rather than as discrete associations or order tags.) And when coding order by familiarity, we would expect that the farther apart two probe items are in the memory list, the less time it should take to determine that the items are correctly ordered because there will be a greater difference in strength (E. E. Smith et al., 2002).

There is behavioral evidence for all three mechanisms. The Burgess and Hitch (1999) model focuses on the serial recall of unrelated words. For example, the participant might see the words *table, lemon, rock, sheet, pen*, and *lunch*, followed by a brief delay, and then be given a signal to recall the words in order. Participants report rehearsing the items to themselves during the delay. This model assumes that successive elements are directly associated, and this model explains behavioral data on serial recall. Here's an everyday case of direct associations: when asked for the last four digits of their Social Security number, which are often requested by various security programs, many people find themselves going through the entire number to get to the fourth-from-last digit. Presumably, they have memorized the number as a sequence of direct associates (try it—have you?).

Other studies supply evidence for order tags. In one experiment, participants were first presented a short sequence of words, and after a brief delay had to perform one of two working memory tasks: recall the words in the order given, or recall the words in alphabetical order. Because the second task requires a reordering of the input order into an alphabetical order, it probably can be accomplished only by a mechanism that assigns alphabetical-order tags to items held in working memory, and then uses these tags to guide recall. Accuracy was high in the alphabetic-order task, which offers some indirect evidence for a direct tagging mechanism. Interestingly, when participants performing these tasks had their brains imaged, only the alphabetized-recall task activated the dorsolateral PFC; the simple input-order task did not result in such activation even though it required representation of the input order (Collette et al., 1999.)

Still other studies provide evidence for the use of familiarity to represent order information. In a representative study, participants were presented five letters in a particular order, followed by a brief delay. The probe that followed always consisted of two letters (Figure 7–17a). There were two tasks: an item task, in which the two probe letters were identical, and the participant simply had to decide whether that letter had appeared in the memory set; and an order task, in which the probe letters

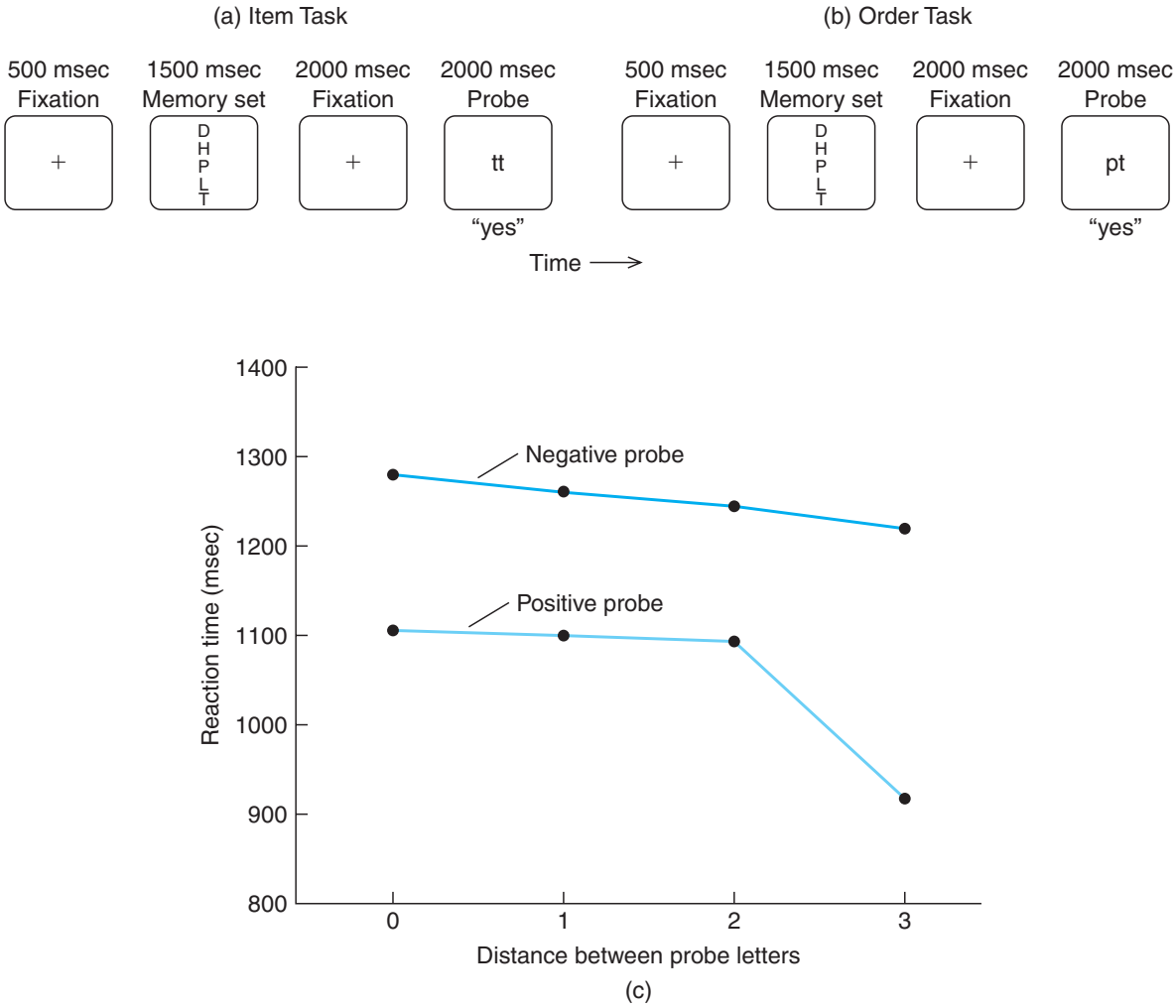


FIGURE 7–17 **Distance effects in order judgments**

(a) The item task and (b) the order task. In both tasks, participants were shown a fixation point (a plus sign) between trials. In a positive probe, the probe item or order matched the memory set; in a negative probe, it did not. Again, in both tasks the probe is in a different case from the memory set to prevent participants from using a visual matching strategy. (c) The distance effects obtained in the order task: the greater the distance between the two probe letters, the faster the response times.

(Marshuetz, C., Smith, E. E., Jonides, J., DeGutis, J., and Chenevert, T. L. (2000). Order information in working memory; fMRI evidence for parietal and prefrontal mechanisms. *Journal of Cognitive Neuroscience,* 12, 130–144.)

differed, but were both drawn from the memory set, and participants had to decide whether the letters were in the same order as in the memory set (they did not need to be adjacent for a yes response). In the order task, when the time to make a positive or negative decision is plotted against the distance between the two probe letters in the memory set, response times decrease with distance—a "distance effect"—as we would expect if relative familiarity or strength were used to make the judgments (Figure 7–17b) (Marshuetz et al., 2000).

When participants performed these same tasks while their brains were imaged by fMRI and the activations for item and order tasks were compared, two regions were more activated in the order than in the item task. One was the dorsolateral PFC, which of course fits with the frontal-executive hypothesis. But the other areas were in the parietal cortex, again showing that certain parietal regions are involved in some executive processes. Even more interesting, some of the parietal regions were in the intraparietal cortex, an area known to be involved in judgments of continuous quantities, such as comparisons of numerosity (Chochon et al., 1999). This fits with the behavioral data showing distance effects. In short, the neuroimaging data provide evidence that people can use two of the different representations of order: a familiarity-based representation that relies on the intraparietal cortex, and a direct temporal-coding representation that is mediated by the dorsolateral PFC (Marshuetz et al., 2000).

6.2. Sequencing Connected Items

Given some idea of how we code the order of arbitrary items, the next step is to consider the sequencing of connected items, as occurs in many real-life situations. It turns out that a critical distinction here is between familiar and novel item sequences.

A familiar real-life sequence is "going to a restaurant." Most adults, like the diners in Figure 7–18, have memorized the sequence of steps in this endeavor, which in the United States goes roughly like this: enter the restaurant, be seated, accept a menu, look over the menu and make a choice, place an order, receive the food, eat the food, ask for the check, pay the check (plus a tip), and leave the restaurant. So familiar is this sequence that Schank and Abelson (1977) dubbed it a *script,* and detailed a number of other scripts (among them "going to the movies," "washing clothes," and "starting a car"). Moreover, there is evidence that our representation of a script consists of direct inter-item associations. When you hear a story about going to a restaurant and some important steps are left out ("Herbie was seated and ate his steak"), the effect is disconcerting. The more steps that have been left out, the longer it takes to understand the story, as if you have to fill in the missing steps mentally before taking in the next one (Abbott et al., 1985).

Things are different when it comes to generating a novel sequence, say, the sequence of activities needed to open a beauty salon. Now you must do some problem solving rather than just rely on associations (Schank & Abelson, 1977). The goal of opening a beauty parlor must be broken down into subgoals, and plans and subplans must be generated. Normal participants have little trouble generating such novel sequences, but it is a very different story for patients with damage in the frontal lobes, particularly the dorsolateral PFC, as shown by the following experiment.

FIGURE 7–18 The restaurant script in action

These diners, at various stages of the restaurant experience, know what comes next, know what to do. Patients with frontal-lobe damage have difficulty with this.

Three different groups of participants were tested on event-sequencing tasks. The three groups included patients with lesions in the PFC, particularly the dorsolateral PFC; patients with lesions in posterior cortical regions; and normal controls. The types of sequences they were tested on included scripts, such as starting a car, and novel sequences, such as opening a beauty parlor. In one study, participants were first asked to generate actions associated with the themes (for example, miming starting a car); then they ordered the generated actions into an appropriate sequence. There were no differences among the three groups of participants in the number or type of actions generated for familiar or unfamiliar themes.

In contrast, notable differences appeared when the participants had to order the generated items into a sequence. None of the normal participants nor the patients with posterior lesions made any errors on the script sequences (such as starting a car), whereas the frontal-damage patients made some errors in sequencing. This pattern was amplified when the sequence was unfamiliar (opening a beauty parlor). Now frontal-damage patients made substantially more sequencing errors than either normal participants or posterior-damage patients (the latter two groups did not differ). These findings show that the PFC is involved in sequencing actions as well as generating them. Exactly the same pattern of results was obtained in a second study, in which participants were given cards with actions for different themes written on them and were asked to order

the actions for each theme. Frontal-damage patients made many errors, whereas normal participants and posterior-damage patients were almost perfect (Sirigu et al., 1995).

These results cannot be explained by assuming that sequencing unfamiliar items is more difficult than sequencing familiar ones and that patients with brain damage will show a deficit in performing a task to the extent the task is difficult. The posterior patients, like the PFC patients, had extensive brain damage, yet they performed relatively normally in sequencing unfamiliar items. So it matters where the damage is, and when it is in the PFC, sequencing processes deteriorate. This study provides good evidence that the PFC (particularly the dorsolateral PFC) is involved in sequencing actions. It also has the virtue of being closer to real-life concerns, given that the kind of sequencing that was studied captures much of the difficulties that frontal patients experience while trying to carry out a job or lead a normal life.

Comprehension Check:

1. What are different ways in which order information may be represented?
2. What is the evidence that the PFC is involved in processing ordered sequences?

7. MONITORING

In the context of executive processes, **monitoring** is the assessment of one's performance on a task *while the task is being performed*. This is to be distinguished from the ability to assess (and improve) your performance *after* the task is completed, either from feedback received or your own view of how things went.

On-line monitoring occurs in a vast number of human activities—whenever you assess how you are doing while solving any kind of problem, intellectual or social (e.g., Metcalf & Shiamura, 1994), or when you check your understanding of the sentence you are reading as you go. Monitoring may be even more "meta" than the other executive processes we have considered; you can imagine situations where you assess whether you are attending well, or switching attention well.

7.1. Monitoring Working Memory

We have already seen a close connection between working memory and a number of executive processes. Some of the most influential work in this area involves the self-ordering task (Petrides et al., 1993a) illustrated in Figure 7–19. In this example of the task, trials are presented in blocks of six. On the first trial a set of six objects is presented, and the participant points to one of them. On the second trial the same six objects are presented, but in a different configuration, and the participant's task is to point to a different object from the one selected earlier. On the third trial, the same six objects are again presented in still a different configuration, and the participant's task is to point to an object that has not been selected before. According to Petrides et al. (1993a), participants accomplish the task this way: they store their

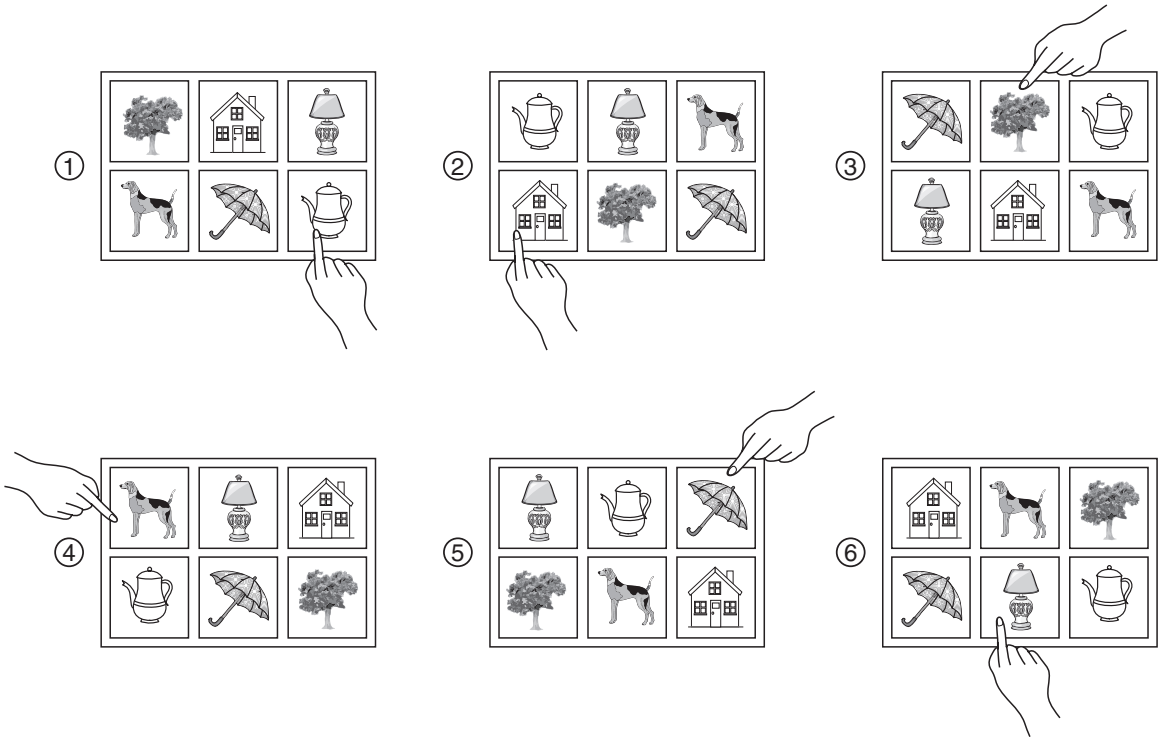


FIGURE 7–19 A correct performance on a six-item self-ordered pointing task

The participant must point to a different item on each page; the position of each picture varies from page to page.

first choice in working memory; then, before making the second choice, inspect (that is, monitor) the contents of working memory so as not to make an error; store their second choice in working memory; and so on. The task involves the constant updating and monitoring of working memory, and it is generally assumed that it is the monitoring part that is critical to success.

Normal participants have little trouble with this task, as long as the memory load is in the range of six (that is, within the capacity of working memory). For patients with frontal damage, it is a different story. Frontal-damage patients are impaired on this task, even when compared to patients with temporal-lobe damage; in contrast, frontal-damage patients are not impaired on a working memory task that requires only reporting the six items presented. Presumably the requirement to monitor the contents of working memory is mediated by the PFC, the left PFC in particular (Petrides & Milner, 1982). This result has wide generality. It holds with verbal items as well as visual ones, and essentially the same deficits can be produced in monkeys that have been lesioned in the region of the dorsolateral PFC (Petrides, 1986). Furthermore, when normal human participants perform the task while having their brains imaged (by PET), one of the major regions activated is—you guessed it—the dorsolateral PFC.

A comparable task is the generate-random task. The task sounds simple enough. Generate a string of, say, eight random numbers. Now, most people believe

that a string of random numbers would have few or no immediate repeats and no discernible pattern (both beliefs are incorrect, by the way). The only way to meet these two constraints while generating "random" numbers is to store each digit produced in working memory, and then monitor working memory before generating the next digit so that you do not get a repeat or produce a pattern. In a PET experiment that compared generate-random to generate-in-order (for example, say the numbers 1 through 8 in order), only the former task activated the dorsolateral PFC (Petrides et al., 1993b). On the face of it, these studies suggest that monitoring is an executive process at least partly mediated by the dorsolateral PFC.

7.2. Monitoring for Errors

Another source of evidence for monitoring as an executive process comes from studies that focus on errors. For openers, there is a good deal of behavioral evidence that participants know when they commit an error in choice-response time tasks such as "push the left button when a circle appears, the right button when the square appears, and push the middle button if you make a mistake." Judging from these behavioral data, error detection can be quite slow, with some studies showing that it takes about 700 milliseconds (Rabbitt, 1998). These times are sufficiently slow that it is hard to take them as measures of on-line processing.

However, work using event-related potentials provides more convincing evidence that participants are detecting errors very soon after making them. Gehring et al. (1993) found a wiggle in the ERP response wave that followed incorrect responses. This component, called the *error-related negativity* (ERN), is a negative deflection in the ERP wave that begins about the time of an error, often slightly before it, and peaks roughly 100 milliseconds after the error. Given how quickly the ERN occurs, it probably reflects some kind of internal monitoring process. One interpretation of the results is that the ERN reflects a process that signals errors whenever it detects a mismatch between the response made and the correct response, where the latter is determined by information accumulating after the initial response has been selected (e.g., Gehring et al., 1993; see also Botvinick et al., 2001). Furthermore, although ERPs do not lead to fine-grained information about location in the brain, it appears that the ERN is being generated by a midline structure in the frontal cortex, presumably the anterior cingulate.

In discussing earlier the neural-network model of executive attention, we considered the proposal that what is being monitored is not errors per se but rather conflict at the response level. The evidence in favor of this position comes from a neuroimaging study. It showed that trials that engender substantial conflict, yet are responded to correctly, lead to increased activation in what appears to be the same region of the anterior cingulate activated in the ERP studies (Carter et al., 1998). The exact interpretation of how on-line monitoring is accomplished remains a hot topic of research, but the findings from both ERP and fMRI experiments leave little doubt that such an executive process exists.

An issue that has arisen repeatedly in this chapter focuses on the question of how many executive processes exist. In closing, we address this question in the Debate Box.

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An issue that has arisen repeatedly in this chapter focuses on the question of how many executive processes exist. In closing, we address this question in the Debate Box.

How Many Executive Processes Does It Take . . .? DEBATE

We have assumed throughout the discussion that there are a number of executive processes and that this number is relatively small—fewer than 10. Although this assumption is shared by many researchers (see Stuss & Knight, 2002), there are other views. Some researchers hold that there is only one executive process, whereas others hold that there are hundreds.

When Alan Baddeley published his model of working memory in 1986 and introduced the notion of a central executive, he had in mind an attentional–inhibition system, similar to what we discussed under the heading of "executive attention." The basic idea (in line with Norman & Shallice, 1986) was that when stimuli are unambiguous or the required response is straightforward, no attention is needed; but when there is any kind of conflict, then executive attention—the central executive—must be brought into play. More recently, the neural-network model initially developed by Cohen and his colleagues (1990) posited only an attentional device as an executive process (the notion of a conflict monitor was added to the model more recently). Because the Cohen et al. model has inhibition naturally built into it, it is capable of accounting for much of the data presented in our discussion of executive attention and switching attention. This type of model clearly has parsimony on its side, but it also has some substantive problems. First, it cannot easily explain why a neuroimaging contrast between an executive-attention task and an attention-switching task has produced some notable differences in activation sites. Second, it is not obvious how this model could account for the sequencing data we presented.

Another argument for a single-executive-process view has been made (Duncan et al., 2000). These investigators imaged participants on a few different tasks that supposedly involved different executive processes, and found that all tasks activated the same general PFC region, the dorsolateral PFC. They concluded that only one process is in play, something like general intelligence (or what is called *fluid intelligence,* that is, the ability to reason about novel situations). Our discussion, too, has implicated the dorsolateral PFC in every executive process considered. But we have surveyed a far greater array of studies than did Duncan and his colleagues, and we have turned up evidence for the involvement of some different neural areas in different executive processes, for example, parietal regions in attention switching, orbitofrontal areas in response inhibition, and intraparietal regions in order judgments.

Those who argue for a multitude of executive processes often do so from the perspective of a computational model, although of the "boxes-and-arrows" information-processing type (e.g., Meyer & Kieras, 1997a, 1997b). Consider a close cousin to task switching; namely, doing two tasks at the same time. For example, a participant may be instructed to discriminate a light (red or blue) and a sound (high or low frequency) simultaneously, and to make the response about the light first. To implement this processing in detail (that is, computationally), one must posit "mini" metaprocesses such as "locking out" the response to the sound in case it comes in first, and then "unlocking" this response when the response to the light has been made. Given the plethora of mini-executive processes that have to be posited, this kind of approach may have the opposite problem from that faced by the unitary modelers. The executive processes in these multiple-executive-process models are often inserted to make the model sufficient to account for data, and it may prove very difficult to obtain independent evidence for their existence. So they explain much, but possibly at the expense of positing too much.

Comprehension Check:

1. In tasks requiring the monitoring of working memory, what neural structure is routinely activated?
2. "We are quickly 'aware' of making an error." What is the evidence for this assertion?

Revisit and Reflect

1. *Are executive processes mediated by the frontal lobes?*

   Early studies indicated that many executive processes are impaired by injuries to the frontal lobes, particularly the PFC. Researchers developed a set of tests that presumably taps executive processes—among them the Stroop, Wisconsin Card Sort, and Tower of Hanoi tests—and showed that patients with PFC damage were selectively impaired on these tasks. These findings strengthened the frontal executive hypothesis, the idea that every executive process is primarily mediated by the PFC. Our review has shown that this hypothesis is too strong: although the PFC plays a role in executive processes, regions in parietal cortex appear to be as important in a number of executive processes, such as attention switching and scheduling.

   ### Think Critically

   - What anatomical properties of the frontal cortex makes it particularly suitable for mediating executive processes? Does this preclude there being another anatomical basis for executive processes?
   - What kinds of jobs could a person with frontal damage perform normally? What kinds of jobs could such a person not perform normally?

2. *What is executive attention, and how can it be modeled?*

   Executive attention is probably the one metaprocess that everyone would agree is necessary for controlling cognition. A huge number of behavioral experiments point to its role in biasing one source of information over another. Progress has been made both in modeling executive attention—as a neural network that includes an attentional controller and a conflict detector—and in determining its neural bases, the dorsolateral PFC and the anterior cingulate. The exact role of the anterior cingulate, however, remains controversial.

   ### Think Critically

   - How could software designers make use of stimulus–response compatibility in devising, say, a new e-mail system?
   - How does the neural network model of executive attention explain the poor performance on the Stroop task of patients with frontal lobe damage?

3. *What is involved in switching attention?*

Switching attention brings more processes into play. Behavioral experiments show that there is almost always a cost to switching, regardless of the task. This cost is presumably due to engaging additional cognitive processes; most of the neuroimaging results on switching attention indicate that additional neural areas are involved during the switch. Some of these additional neural areas are the same ones involved in executive attention—dorsolateral PFC and the anterior cingulate. (In the relevant studies on switching, these two areas were not involved when performing one task for an entire block.) Other additional switching areas are in the parietal cortex.

Think Critically

- As discussed in Chapter 3, some researchers have proposed that attending to something is like shining a spotlight on it; if so, then switching attention would be like moving the spotlight. Consider a behavioral prediction about task switching that this analogy suggests to you.
- Imagine an experiment in which on alternating trials participants had to do a Stroop task ("name the ink color") and a reading task ("read the word"). How would the information-processing model describe the underlying processing? How would the neural-network model describe it?

4. *What is response inhibition, and what is distinctive about it?*

Response inhibition, the suppression of a partially prepared response, can be isolated experimentally by tasks such as go/no-go and stop-signal. These tasks show that participants are sensitive to the probability of a go response or the time to delay a response. At the neural level, these tasks activate the dorsolateral PFC and the anterior cingulate. However, these tasks often bring an additional area on line, the orbitofrontal cortex. In addition, there is a remarkable parallel between the participant's ability to inhibit a response and the development of the PFC.

Think Critically

- Can you think of any real-life situations in which it is adaptive to be impulsive, that is in which it is adaptive *not* to exercise response inhibition?
- Suppose the PFC were fully developed by age 2. What would be some of the implications for child rearing?

5. *What mechanisms are used for sequencing information?*

Three different mechanisms may be used in sequencing unrelated items, including associations between adjacent items, direct coding of temporal order, and using relative familiarity to code order. Neuroimaging studies support the idea of different mechanisms: the dorsolateral PFC may mediate direct coding of order, whereas the parietal cortex may mediate the use of continuous information—such as the relative strength or familiarity—to code order. In sequencing related

items, there is an important distinction between constructing familiar versus novel sequences; the operation of the PFC is sensitive to this distinction, as indicated by the fact that frontal-damage patients are far more impaired on generating a novel sequence than a familiar one.

Think Critically

- When might it be advantageous to code for order by using the relative familiarity of the items?
- What is the difference between sequencing and coding order?

6. *What is involved in monitoring our performance "on-line"?*

Work on monitoring as an executive process has followed two lines of research. One focuses on monitoring the contents of working memory; the PFC is clearly involved. The other focuses on monitoring for errors, a process that has been well studied in behavioral experiments. In addition, ERP and fMRI studies suggest that such monitoring is extremely rapid, occurring within 100 milliseconds of the response, and that the process is mediated by the anterior cingulate.

Think Critically

- Is there any difference between *monitoring* the contents of working memory and *attending* to the contents of working memory?
- What are some of the advantages of being able to monitor for errors on line?