

C H A P T E R

Measuring Mind

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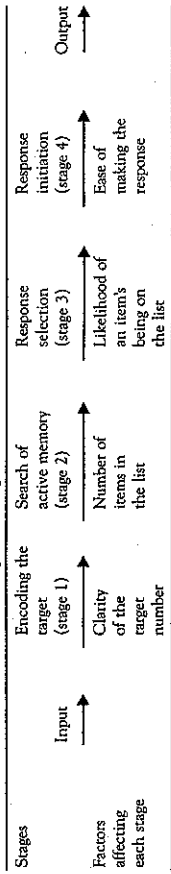
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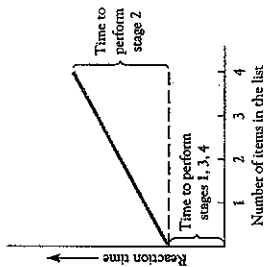
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In these days of computers it is commonplace to think of human thought and human actions as slow. However, this view was not always widely held. Until 1850 the speed of neural conduction was believed to be at least as fast as the speed of light. Johannes Mueller, a famous German physiologist of the mid-nineteenth century, asserted that the speed of neural conduction would never be measured. While we had the whole heavens in

Component Operations in the List Task



The length of the list influences only the second of these serial stages: searching active memory. Sternberg argued that any variable that affected a different stage would have the same effect on overall reaction time for all list lengths. For example, if the clarity of the target number you are shown is reduced by making it dimmer, reaction time is also lengthened, but this change in reaction time is the same whatever the list length. Sternberg thus argued that the stage of encoding the target, which was affected by its clarity, was independent of the stage that varied with list length. In general, if a task consists of a set of serial stages, it is possible to examine the degree to which any particular experimental manipulation affects each of the stages. If two variables affect different stages, their influence on the overall reaction time will be additive. This approach makes it possible to isolate the operations present in any stage. For example, stage 2 apparently consists of a search performed by comparing the target with the items stored in the list. The additive factors method is one example of an effort by psychologists to isolate underlying processes by showing that one process can operate independently from another.



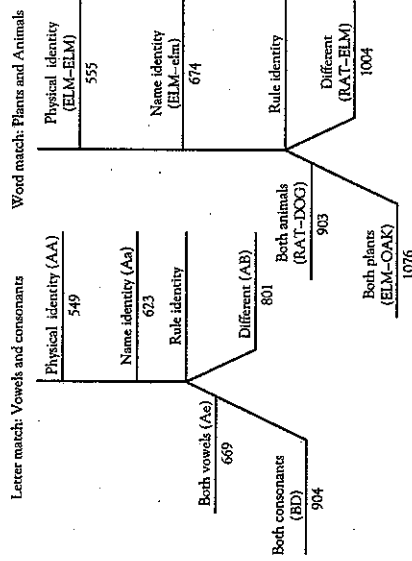
Sternberg's additive factors method for isolating serial stages is applied here to the task of identifying whether an item is a member of a just-presented list. The reaction time increases as the number of items held in store is varied from 1 to 4 items, but this number affects only the time it takes to perform stage 2, a search of the list for the targeted item.

performance of a variety of tasks such as walking and talking, some of which involve cognitive processes. Suppose we want to know what aspects of the performance of patients suffering from Parkinson's disease are slowed. Can we conclude that the disease slows the person's thought processes, or does it solely influence the motor system? To study this question we compare the performance of Parkinson's patients with that of normal subjects in the memory search task just described. We already have evidence from normal subjects that this task has a serial structure, and we know some of the variables that influence each stage. If Parkinson's patients are slower by the same amount for all list lengths, we can conclude that the disorder does not affect the rate at which memory is searched, but must influence encoding or responding. If further studies show that Parkinson's patients are affected the same as normal subjects by degrading the stimulus, which affects encoding, but are affected more than normal subjects when a strong force is needed to press the key, purely motor operations must be slowed by the disease.

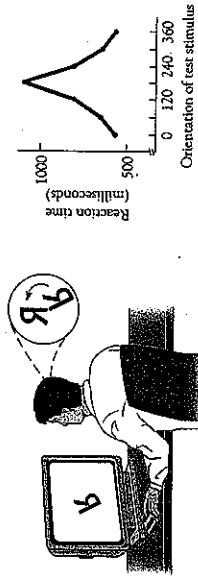
This example shows that designing a task to have a serial structure can help us specify how unknown conditions influence internal mental operations. Sternberg's method provides a rigorous procedure for isolating the mental operations in such tasks. It is more usual, however, for the operations that make up everyday tasks to be performed in overlapping or parallel fashion, rather than purely in serial. In these cases one cannot apply the additive factors method, but it still may be possible to isolate two separate operations by showing that a variable that affects the time for one operation has no effect on the other, and the reverse.

The simple act of addition provides an example of the brain's tendency to perform more than one operation at the same time. Suppose we ask you if $4 + 3 = 7$. It will take you about 20 milliseconds longer to determine that this sum is correct than for you to determine that $4 + 2 = 6$, even though both calculations seem immediate. The operation apparently takes longer when the smaller of the two numbers increases. Could we be incrementing the larger number (4) one count at a time until we have reached the smaller (3)? Perhaps, but this cannot be the only process. It will take you longer to decide whether $4 + 3$ equals the false sum of 12 than the false sum of 11 or 13. At the same time that you are determining the sum of 4 and 3, your brain also seems to "look up" other common associates such as the product of the numbers, even though you may be completely unaware of its doing so. In performing mental tasks, our minds seem to use a combination of slow deliberate serial computations and rapid parallel "lookup."

Even when operations are performed in parallel, it is still possible to design methods to isolate them from the overall task. Although one cannot apply the additive factors method, it still may be possible to show that two operations are dissociated by manipulating them independently. A good example of a task requiring parallel operations is the activity of recognizing letters or words. The figure on this page illustrates the times required to recognize whether a pair of simultaneously presented letters or words belong to the same category (for example, both vowels or both animals). The reaction time to match pairs of items that are physically identical (for example, AA) is faster than the reaction time to match pairs of the same letters or words when the two are in different cases (for example, Aa), which in turn is faster than the reaction time to match pairs of items that share only the common category (for example, Ae, both vowels). There are reasons for supposing that the match AA is accomplished by matching visual codes rather than letter names. If the color or size of one of the two letters is altered, for example, the time needed to match letters of the same case increases, but the time needed to match letters of different cases is not changed. On the other hand, if the match must be made while holding other letter names in memory, the time for cross-case matches is increased,



Subjects may be asked to match pairs of letters (left) or pairs of words (right) that share a physical (e.g., AA), name (e.g., Aa), or conceptual identity (e.g., Ae). The reaction times for each decision are given in milliseconds.



Asked to respond as quickly as possible whether a target letter is a real or mirror image letter, the subject rotates the image in his head to an upright position before making the decision. The farther the letter's initial orientation is from upright, the greater the reaction time.

although there is little or no evidence that matching times for identical pairs is also increased. Thus, cross-case matches are probably made by comparing letter names. By tests such as these, the operations taking place on the visual code of the letters can be isolated from those taking place on the phonological code.

While operations performed on a visual code are likely to be faster than those performed on a higher-level code such as the letter name, this is not always the case. This is shown clearly by studies of Roger Shepard and Lynn Cooper, then at Stanford University. Suppose you were shown a letter appearing at an angle and asked whether the letter would be either a correctly oriented letter or a mirror image if it were turned upright. The reaction time for this task increases with the angle of rotation in a roughly linear fashion, as shown in the graph on this page. Nonetheless, the angle only slightly affects the time required to identify which letter is being shown. It takes quite a bit longer to perform the internal rotation necessary to tell if the letter is a mirror image than to know which letter it is. Identifying the letter is quick because you are finding the letter name while still performing the rotation, whereas the orientation of a letter cannot be judged until after the rotation is complete. This finding clearly indicates that operations on the visual code and on the letter name are not performed in serial stages, but in parallel. Nonetheless, one can experimentally manipulate the required time to perform each type of operation independently of the other. Changing the color or angle of rotation of the letters mainly influences operations on the visual code, while making the names similar (for example, c, d, p) influences operations on the letter names.

Although it is possible to isolate mental operations by independently manipulating their performance times, these cognitive studies are not unambiguous. For example, it seems likely that even cross-case matches can be made not on the basis of the letter names, but because you have learned to visually identify letters of one case with letters of the other. When you answer questions about your memory of friends (e.g., do they wear glasses?), it is possible that you are using stored verbal information about them instead of consulting a visual code. There is a built-in ambiguity about the source of measured effects such as changes in reaction times or other general performance measures. To resolve this ambiguity we would like to be able to determine whether and what different brain areas are active as these operations are performed, especially in complex real tasks like reading. In fact, we will be examining exactly that issue in Chapter 5. Before doing so, however, we consider the more general logic of how scientists establish relationships between cognitive activity and underlying brain mechanisms.

FROM THOUGHTS TO CELLS

In thinking about how to establish links between mind and brain, scientists find it useful to conceive of five levels of analysis, which descend from the broadest structure of the mind to the smallest units of the brain. These levels of analysis are cognitive systems, mental operations, performance, neural systems, and cells. The framework provides a convenient way to compare research findings gained by various methods at different levels of analysis. While we concentrate in this chapter mostly on mental operations, human performance, and neural systems, it is worth considering all of the different levels that play a role in the chapters ahead. In so doing, we will gain a sense of the whole pattern from complex cognitive processes to the findings of individual neural cells.

Cognitive Systems

At the highest level are the activities of everyday life. These include such familiar tasks as reading, writing, recognizing faces, daydreaming, moving from place to place, playing music, and planning a trip. A very long list of such tasks could be constructed. There is a great deal of evidence from patients suffering from different forms of brain damage, however, that these tasks may be roughly grouped together into a number of "cognitive systems."

Framework for Linking Cognitive and Neural Levels of Analysis

Level	Example	Methods
Cognitive system	Language, attention, motor control	Verbal report
Mental operation	Next, rotate, zoom	Computer simulations
Performance domain (pathway activation)	Facilitate, inhibit	Cognitive studies, neural networks
Neural system	Parietal lobes	PET, event-related potentials, MRI, lesion analysis
Cell	Primary visual area	Cellular recording

The idea of a cognitive system has some analogies with an organ system. Respiration, for example, is performed by an organ system that consists of the nose, lungs, and other organs and that performs the particular function of maintaining oxygen levels. Like respiration, a cognitive system is a set of structures that operate together to perform a general function. For example, reading, writing, speaking, and conversing are all tasks of daily life, and they all involve the cognitive system that we call "language." We know that this system involves several brain structures, because damage at various locations of the left hemisphere impairs aspects of this language system. Sometimes "planning ahead" is thought to involve a separate cognitive system. Lesions of the frontal lobes often impair planning, and thus there may be a brain system that underlies this activity. Similarly, selective attention appears to depend on particular brain systems.

Mental Operations

In the last 20 years, cognitive psychologists have subjected complex cognitive tasks such as playing chess, reading, and manipulating visual images to detailed analysis. These analyses have divided a given task into operations that might form the basis for programming a computer to simulate

human performance. For example, the table on the facing page depicts part of an analysis of the task of imagining that you are walking along a familiar route from the work of Stephen Kosslyn at Harvard University. Each of the proposed operations has an input, a computation, and an output, so each operation performs a specific cognitive function. When these operations are organized into an appropriate sequence, one has a computational model of the type used in artificial intelligence and that is theoretically capable of performing tasks requiring visual imagination.

Such analyses attempt to construct a logical set of operations that would be sufficient to simulate the task being studied. Each operation may thus be thought of as a subroutine for the computer. The logical analysis may or may not correspond to what happens when people actually perform the task, but it does show that the task can be analyzed into a set of subroutines sufficient to perform it. When a computer can actually be programmed to perform the specified task, there is evidence that the logical analysis chosen is at least internally consistent.

The Performance Domain

The next step in our effort to link cognitive processes to neural systems is to ask how a human mind actually performs the postulated operation. To achieve this goal, we need to apply the previously discussed methods designed to isolate operations. First, we need to design a model task that incorporates the operations which we want to study. The task of isolating the mental operations is easier if the model task is simple. If the task is structured so that operations are performed in serial, we can use the additive factors method, but more generally we can attempt to manipulate the underlying operations independently.

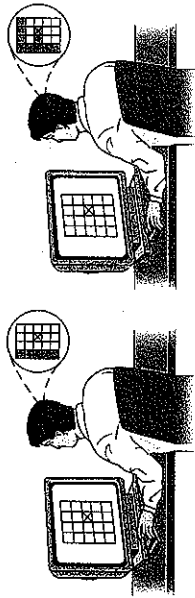
Consider the formation of a visual image. Suppose you are presented with the letter name "f" and asked to form an image of the letter that would fill the grid depicted in the illustration on page 40. Can we tell how you are doing it? We can't simply ask you to describe in detail how the image is constructed because you have little insight into that level of processing in your own mind.

In order to discover how you mentally generate the "f," we design a model task. You are asked to determine as quickly as possible whether a probe mark on the grid falls on or off the image. Immediately after the presentation of the "f," you are slow to verify whether or not the probe lies on the image because you have not yet created the image. After a short delay, you are fast to verify probes that lie on the upright of the "f," but slow

Some Mental Operations Involved in Creating Visual Imagery

Name	Input	Operations	Output
PICTURE	Name of a literal encoding stored in long-term memory (and desired size, location, and orientation)	Produces a pattern in a temporary visual memory store called the visual buffer; may vary the size, location, and orientation	A visual image of the named perceptual unit (a part or the general shape of an object)
FIND	Name of a sought part; image in the visual buffer	Looks up a description of the part; looks for the pattern corresponding to the named part	Locate/not locate decision; if finds, indicates the location of the part in the image
PUT	Name of the part to be added to the image in the buffer	Looks for the image encoding of the part; if locates, then looks up description of the relation and the foundation part; then invokes FIND to locate the foundation part in the image; computes size and location values for the new part; provides PICTURE with these values and the name of the literal encoding of the part to be imaged	Part integrated into the image at the correct size and location
ROTATE	Image in the visual buffer (and the desired angle, direction, and rate of rotation)	Shifts the image around a pivot; uses FIND to monitor progress. May be set to rotate in a specified direction, angle, and rate	Reorients the imaged pattern, part, or object
SCAN	Image in the visual buffer (and the desired direction and rate of scan)	Shifts the image through the visual buffer; fills in new material along the leading edge; uses FIND to guide path	Imaged material is shifted so that the new portion is in the central, most acute part of the buffer

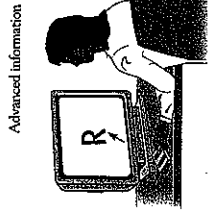
A subject mentally constructs an image of an *r*, one stroke at a time, within the grid lines in order to determine whether a probe *X* is on the imagined figure.



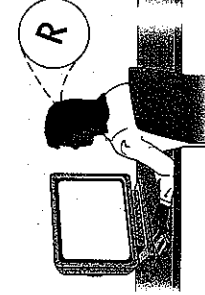
to verify those on the cross bar. It is as though you have generated the left part of the image but not yet the rest of it. In fact, the letter image appears to be generated stroke by stroke, in the same way as you would print it. What is most remarkable is that as you construct the image you improve the speed at which you verify that the probe lies on a stroke that has already been generated.

To take another example of how the performance of a mental operation may be analyzed, suppose you are presented with an upright letter (e.g., *R*) and asked to rotate it counterclockwise in your mind's eye. Are you actually performing the rotation? To test whether you are, we probe with letters at varying angles from the upright. You are asked to report by pressing one key if the probe is a correct letter and another key if it is a mirror image letter. Before starting a trial, we provide you with some advanced information. For example, suppose we tell you the identity and the orientation of the letter; then present the probe letter after a delay. You will respond to all probes equally quickly, regardless of the angle, because thanks to the advanced information you no longer have to rotate the probe letter to an upright position to tell if it is a mirror image.

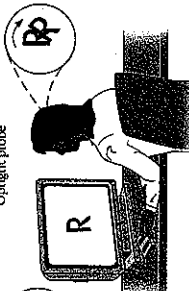
Now suppose that on some trials we show you probes having an orientation different from the advanced information. The results are even more remarkable than before: the reaction times to probes now depend on how distant they are from the orientation provided in the advance information. Suppose you are given information to anticipate an *R* at 30 degrees. You are actually faster in responding to a probe at 30 degrees orientation than to one that is upright at the usual angle at which we view letters. You have used the advance information to obtain a representation of the letter at the angle supplied; when shown the probe letter, you rotate it to the angle of that representation, then make your decision. Your use of the advanced information has objective consequences that can be measured precisely by observing the time needed to verify the probe, and these consequences are



Advanced information



Upright probe



strong enough to overcome the usual preference for upright letters based on past experience.

In the previous two examples, the experiments studied how the speed of processing was improved, or, to use another term, facilitated. The performance of respondents in the first model task was facilitated as they constructed the letter, in the sense that the speed improved at which they verified the placement of the probe. In the second model task, performance was facilitated when a probe letter's angle of rotation corresponded to the degree of mental rotation. It is possible to study not only facilitation in performance but also inhibition. Inhibition in performance is a reduction in the speed of processing a stimulus; it is often measured as an increase in reaction time to the stimulus. Alan Allport and Steven Tipper then at Oxford University developed a method to show this form of inhibition. In the margin of the next page is a series of red letters on top of green letters. Suppose you are asked to name each of the red letters, while ignoring the green letter below it. Was it difficult to name the *S*? You might not have noticed, but your reaction time to name the red *S* is greater than it would have been had not the *S* just been viewed in green. When you select the red item you also inhibit the green one. The inhibition remains present for a period of time and retards your performance on the subsequent item.

These experiments have shown that the performance of a mental operation can be observed by examining facilitations or inhibitions in the speed of processing probe items, using measures such as reaction time. We call this level of analysis the performance domain. The basic idea is that a pathway is followed through the brain as a target stimulus is processed; this pathway can be either facilitated (pathway activation) or inhibited by prior events that have altered the ease with which the target stimulus can access various internal codes. For example, in the rotation task, knowing the orientation of a letter in advance allows you to access the visual code of the letter more quickly.

In addition to measuring the time required for processing, there is a second objective method for studying the performance of mental operations. When two mental operations compete for the same internal mechanism, they require extra time. In this case, the operations interfere with each other's performance, a more general form of inhibition than that seen in the previous example. To explain this feature, consider a task involving a hypothesized internal clock, from the work of Steven Keele of the University of Oregon. In this task, subjects listen to a tone that occurs every half second and are asked to tap a key in synchrony with it. After the tone is turned off, they continue to tap at the same interval. Performance in this task is measured by the variability of the key presses. Initially, subjects perform the task by itself, but they are then asked to do it at the same time as they perform one of two secondary tasks.

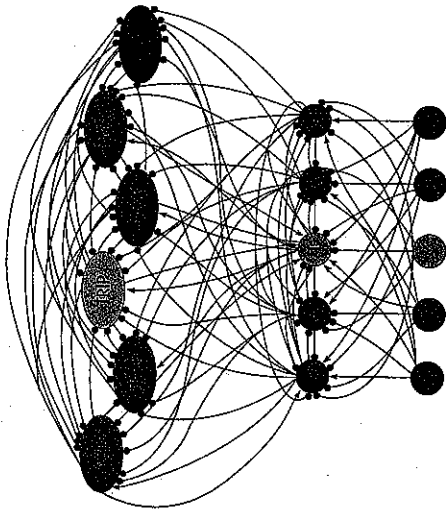
Both secondary tasks require the subjects to respond to two pairs of tones, presented after the original sequence of tones has stopped and while the subjects are still pressing the keys. One secondary task is to determine if the interval between one pair of tones is the same as the interval between the second pair. The other secondary task is to judge if the difference in loudness between one pair is the same as that between the second pair. Both secondary tasks are designed to avoid the same stimulus input and motor responses as the primary task, and both are equivalent in difficulty and demand the same amount of attention. The major difference is that judging the interval should require the hypothesized clock, whereas judging the loudness should not. Experiments show that the secondary task of judging the interval interferes much more with the primary task than does the task of judging the loudness. Thus when both mental operations require the clock, performance is greatly degraded, revealing an underlying hidden operation thought to involve this clock, which would be common to both perception and action. The use of simultaneously performed tasks has played an important role in the objective measurement of mental operations.

There is a class of computer models called "connectionist" models that can simulate human performance by simulating the underlying facilitations and inhibitions. The computer program contains weights that indicate the strength of connections between internal units. Performance is facilitated by an increase in a weight and inhibited by a reduction. For example, a number of these models have simulated the performance of word reading. These models can be trained to decide correctly whether a set of letters is a true word. The researcher indicates to the model what the correct response on a trial actually is, and the program adjusts the weights to improve subsequent performance. After many training trials the weights on the internal units

If you try to name the red S in position 5, for example, you are slowed because the letter to be named had been suppressed on the previous trial because it was green.

↓ F ↓ S ↓ A ↓ N ↓

According to one "connectionist" model of how a visual word is perceived, the visual features, letters, and words that form the "nodes" of the model are interconnected by many different parallel pathways. The connections are simulated by weights that indicate how strongly each node excites or inhibits the other nodes.



come to reflect aspects of the stimulus important in making the discrimination. The figure on this page is from the work of Jay McClelland and David Rumelhart, then working at the University of California, San Diego. In this figure the units reflect visual attributes, letters, and words. Once the training trials have been completed, such models are used to predict responses to new items and tasks. These simulated results can then be compared against the actual behavior of human subjects in experimental tasks to see if the simulation really mimics the performance of human beings.

Neural Systems

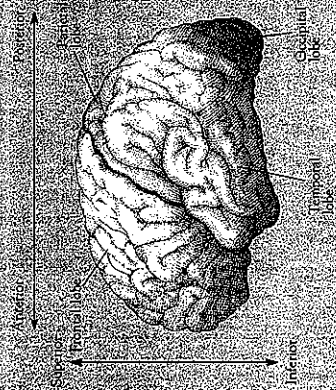
Scientists have found indications of facilitation and inhibition in the performance domain and in connectionist models. To what extent are these findings actually related to underlying changes in populations of neural cells? A traditional approach to this question has been to study patients who have suffered strokes or tumors that create areas of dead neurons called lesions. One then tries to relate the damaged area of the brain to particular cognitive operations. Take the operations involved in reading, for ex-

Some Basic Anatomy

Of the brain's many structures, surely the ones most familiar to the ordinary person are the two dominating cerebral hemispheres. At the lower left, the left hemisphere is portrayed in a lateral view, as though the left skull had been removed, exposing the outer surface. As the diagram shows, anatomists distinguish four major lobes within each hemisphere: the frontal, parietal, occipital, and temporal. Nerve cells are most densely packed and interconcentrated in the outermost 3 millimeters of the cerebral hemispheres, called the cerebral cortex. Although the cortex is not deep, it takes up a substantial portion of the cerebral hemispheres, as it follows their many convoluted folds.

Below on the right, the brain is shown in a medial view, as though a knife cut had separated

the two hemispheres. In addition to the cerebral cortex, the brain contains a dense, ball-shaped mass of matter known as a brain stem, which is composed of three major structures: the midbrain, pons, and medulla oblongata. The midbrain is located in the upper part of the brain stem, the pons in the middle, and the medulla oblongata in the lower part. The medulla oblongata is continuous with the spinal cord.



This lateral view of the brain shows the four lobes of the left cerebral hemisphere.



This medial view of the brain shows the brain stem and corpus callosum.

ample. Difficulties in reading following brain lesions are not uncommon; such difficulties are called acquired dyslexia, since a person who could read normally in the past is now unable to do so. Three major forms of acquired dyslexia have been reported: visual dyslexia, phonological dyslexia, and semantic (or deep) dyslexia.

Visual dyslexics appear to have difficulties integrating the letters of a word into a unit. Some patients appear to read letter by letter, for example. These patients have relatively little difficulty in seeing each letter, but can only grasp the word as a whole when they sound the letters out. For these patients, whether a letter string is a real word ("pearl") or a pronounceable nonword ("tweal") makes relatively little difference, but they do have special difficulties with irregular words. For example, they might pronounce "have" to rhyme with "wave." When the disorder affects reading only, the lesion appears to involve the left posterior occipital or temporal lobe.

A rather different form of visual dyslexia arises in cases of lesions in the posterior parietal lobe. Immediately after a stroke affecting this area, patients show striking deficits that are described as "neglect." Each hemisphere receives sensory information from the opposite side of space, so a lesion on one side of the brain hinders the patients from seeing or feeling on the opposite side: they fail to orient to people who approach them on the side opposite the lesion, and they often neglect parts of their own body opposite the lesion. They will shave only one half of the face, fail to eat food on one side of the plate, draw only one half of a figure when asked to copy it, and even deny that the arm opposite the lesion belongs to them. Many of these striking deficits disappear in the weeks following the lesion as metabolic changes induced by the stroke begin to reverse back to normal in areas remote from the cell death.

These patients have difficulty reading because they often fail to orient to parts of the page opposite the lesion. When asked to read a string of letters, they often fail to report those letters in the string that are on the side opposite the lesion. Patients with right parietal lesions tend to start part way into the string, missing the first few letters, while patients with left parietal lesions will miss the ending letters. However, the brain systems that integrate letters into words appear to be relatively intact, and their activity can even reduce the degree of neglect that otherwise might be experienced. If patients are asked to read letters that form a meaningful word, for example, they may report the word correctly even though they miss letters at the same location when the letters are in a nonword string.

Patients with phonological dyslexia, on the other hand, appear to have lost the ability to sound out words based on the rules of the language. These

patients may be able to read even highly irregular words like "pint" correctly, but have great difficulty pronouncing nonsense strings like "calk" even when they could correctly pronounce the corresponding word "cake." Patients with phonological dyslexia have relatively intact connections between the visual and semantic systems, but not between the visual and pronunciation systems.

Finally, a few patients have great trouble reading words correctly because they make systematic semantic errors. When shown the letters CAT, these patients may respond "dog" or "rat" or give any other word having a strong semantic association with the word "cat." The patients often have massive lesions in the left hemisphere, and the disorder may represent the residual semantic output from the intact right hemisphere. Since the right hemisphere is thought to have a less-explicit semantic system, the patient makes errors by naming related items that are facilitated by the word actually presented.

That deficits in performance vary with lesion locations supports the existence of links between the performance level and specific neural systems. Moreover, these links are not confined to brain-damaged patients, but also suggest properties of normal word reading. For example, in normal people a word tends to facilitate the activation of related words. When brain areas that code the visual and phonological aspects of an input word have been destroyed, patients mistake a word they have seen or heard for another word that is semantically related to the input word. This suggests that it is possible for a word to activate its associated words without its identity ever being represented in the mind by a visual or phonological code. Similar evidence of semantic activation without recognition of word identity can be found in normal people when a word is severely degraded so it cannot be explicitly identified but can still be shown to facilitate processing of a subsequent semantically related test word.

However, there are many difficulties with the logic of the lesion method of localizing brain activity. It is not always clear that a missing function actually represents activity in the lesioned area, since the lack of function might instead be an adaptation of the remaining system to a missing part. Immediately after a stroke a widespread pattern of metabolic changes is observed throughout the damaged hemisphere, and thus the symptoms might reflect these changes instead of or in addition to the death of cells in the area of the lesion.

To overcome these difficulties and to investigate further the links between cognitive operations and neural systems, we turn to modern neu-

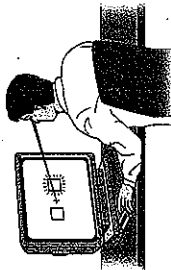
roimaging methods. We apply positron emission tomography, the recording of event-related potentials, and other neuroimaging methods while subjects perform tasks of the type discussed above. These methods allow us to picture the neural systems actually involved as mental operations are performed, in contrast to studies of patients with brain lesions, which examine the operation of the brain with one or more areas removed. We expect that facilitation and inhibition in performance are the result of changes in the underlying neural systems; if that is true, blood flow and electrical activity should change when information processing becomes more or less efficient as measured by reaction time and other behavioral measures.

The Individual Cell

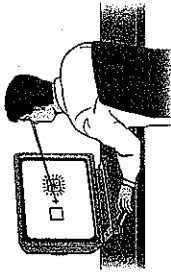
We have traced the framework laid out in the table on page 37 from the level of cognitive systems to the level of the underlying neural systems. The final level is that of the individual cell; this level can only be studied using invasive methods such as microelectrode recordings, which cannot be applied to human beings. Thus, scientists wishing to move further into the heart of neuroscience methods must have nonhuman animals performing cognitive operations. It is not always easy to construct appropriate tasks for animals because many types of cognition (such as reading) are obviously unique to human beings. But successful experiments on animals have been performed to study visual spatial attention, which is the act of attending to a location in the visual field.

In normal vision, when an interesting object is noticed, the eyes move so that the object falls on the central portion of the retina called the fovea, where vision is most acute. While the eyes remain fixed on that location, attention may also remain fixed there, or it may move around the visual field until a new area of interest away from the fovea is found that might become the target for the next eye movement. Thus, subjects do not necessarily focus their attention on the spot where the eyes are fixed: they can give priority either to the location where they are looking or to any other single area of the visual field.

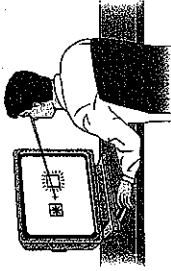
Shifts in attention that occur independently of eye movement are called "covert." These shifts are quite rapid in comparison with eye movements. It usually takes 200 to 250 milliseconds to move the eyes to inspect a new location, but covert shifts in attention require less than 50 milliseconds. If attention shifts to an object that demands high acuity to inspect, it is likely that the eyes will move to that location about 200 milliseconds



Cue given



Target on cued side



Target on uncued side

A model task for studying selective attention first uses brightening to cue the subject's attention to one of two peripheral boxes (left). A target then appears on either the cued side (middle) or uncued side (right), and pressing the key automatically causes the reaction times to be recorded.

after the attentional shift. When the eyes do move, attention and the fovea are directed to the same location until attention shifts again, as the subject examines new locations in preparation for another shift of eye movement.

To study how cells respond during shifts in attention, we first need to select a suitable model task. The model task should allow us to isolate mental operations in a way that also allows us to study neural activity. An optimal task would involve mental operations that are important to a cognitive system, and it would be simple enough for animals or brain-injured human beings to perform.

One useful model task allows the internal mechanisms of selective attention to be studied in the absence of head or eye movements. If not eliminated, these movements would affect reaction times, obscuring the underlying mechanisms used for covertly attending. In the model task chosen, subjects view a screen having a stimulus in the center and two boxes in the periphery. Initially, a brightening of one of the two peripheral boxes summons attention to that box, but human and monkey subjects are trained to keep their eyes fixed on the central stimulus.

The subject's task is to respond as rapidly as possible to a target event whether it occurs in a brightened box (cued side) or on the opposite side. In some experiments, the target is very likely to occur on the cued side, thus giving the subject an incentive to attend there. In other experiments, the target is equally likely to occur on the cued side or the opposite side. In still other experiments, the target is far more likely to occur on the uncued than on the cued side.

When attention is focused at a particular location such as the cued box, the visual processing of targets at that location is facilitated: the subject responds to targets at that location more quickly, and can detect targets that are too dim to be noticed at other locations. Moreover, electrical ac-

tivity recorded from the scalp is amplified. It is as though attending to a location gives increased emphasis to targets at that location.

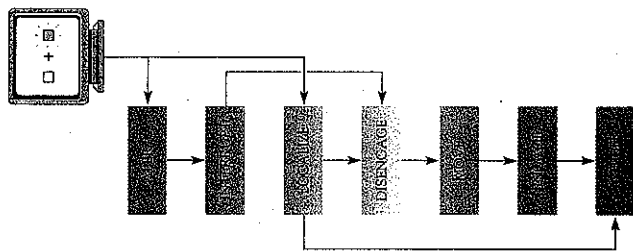
Although subjects process a target quickly at the cued location, attending to that location causes them to respond more slowly to events elsewhere in the visual field. It takes time to disengage attention from the cued location, and the delay produces slower performance at uncued locations. Thus, performance is facilitated at the location attended to and inhibited at other locations. When an area of the visual field has been attended to and a new area is now being inspected, attention will be less likely to return to the previously attended location than to other locations in the visual field. This "inhibition of return" helps to support the movement of attention to novel locations.

The role of the cue in directing attention to the target has been analyzed and a series of mental operations hypothesized, as outlined in the figure on this page. The last four operations have been extensively studied, both in normal and brain-injured persons.

Patients with lesions of the parietal lobe reveal a deficit in this model task that is most closely related to the DISENGAGE operation. These patients easily attend to peripheral stimuli when their attention is not engaged elsewhere, but once they attend to a location they do not respond well to new targets that are on the side of their current focus of attention opposite the lesion. This form of deficit suggests that the parietal lobe is involved in disengaging the subjects' focus of attention. These patients are also the ones described above as having neglect dyslexia, since they fail to report letters or words on the side opposite the lesion. Their failure in reading is completely consistent with their performance in the model task.

In normal people, information passes back and forth between the two hemispheres through a large band of fibers known as the corpus callosum. Normal subjects search stimuli at the same rate whether all targets are presented to one hemisphere or both hemispheres because they have a unified attention system. Patients with lesions of the corpus callosum do not appear to have a unified attention system. Instead, they perform as though they have two dissociated attention systems. Information to the right of where the patient is looking goes directly to the left hemisphere, and information to the left goes to the right hemisphere. Patients whose corpus callosum has been cut search a complex display more rapidly if half of the display is presented to each visual field. It is as though they are attending separately to each visual field.

Normal monkeys perform the model task described above just as do normal adult human beings. Their reaction times are faster for targets at



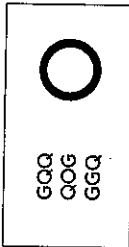
This set of mental operations is thought to take place when a cue indicates where in the visual field one is to attend. The last four operations are discussed in this chapter. The cue interrupts the subject's attention at its current location, causing the subject to disengage attention. The MOVE operation changes attention to the location of the cue. The ENGAGE operation causes firing to be enhanced in the cortex at the location corresponding to the cue.

the cued location than for those at noncued locations, and they also inhibit a location once attended. Although they do not seem to have quite as much cognitive control over where they fix their attention, the findings in the model task are mostly identical to those for humans. Unlike humans, however, monkeys can be studied at the level of the individual neuron.

Single nerve cells are studied mainly by recording from electrodes inserted deep into the brains of alert animals. These animals are cognitive in the sense that they are in active contact with the real world. They scan their environment and respond to stimuli. Recordings from electrodes have found individual cells in several areas of the brain that are involved in attention. Cells in the posterior parietal lobe, for example, increase their level of activity when the monkey is trained to attend to events at areas of the visual field to which those cells are responsive. If the animal is taught to maintain eye fixation but to attend to a location away from the point of fixation in order to detect a dim target, cells receiving information from the area of the target increase their rate of firing to that target more than when the monkey attends to another location. In other words, attention acts to enhance the firing of individual cells. The rate of firing rises within 100 milliseconds after the target appears and is accompanied by improvements in reaction time similar to those observed in human beings. If the parietal area of the monkey brain is lesioned, the monkey displays much the same difficulty in disengaging from a visual stimulus that is displayed by human patients with damaged parietal lobes.

Another area of the brain shown to have cells involved in selective attention is an area in the midbrain called the superior colliculus, which is involved in making eye movements. Patients with lesions in this area show a disruption of both eye movements and covert shifts of attention. Their attentional disruption is most closely related to the MOVE operation, which, although covert, appears to take advantage of the same neural machinery used in overt movements of the eyes. In addition to suffering a disruption of the MOVE operation, these patients also tend to lose the preference for novelty that we call inhibition of return. Having examined a visual location, they are as likely to return to it as to inspect a novel location.

Cells in an area of the thalamus called the pulvinar also show enhanced firing when subjects attend to stimuli. Patients with lesions of the thalamus have problems performing covert shifts of visual attention. These patients appear to have a special difficulty separating information about a tar-



The left half of the display requires the subject to filter out irrelevant details to report the presence of an O, while the right half of the display allows the subject to report the target O without restricting attention to any location.

get from surrounding distractors, especially when the target appears on the side opposite the lesion. When presented with the chart on this page, these patients would find it difficult to report the O because of the surrounding letters. It is as if such patients cannot confine their report to the particular location of the target.

These findings provide support for the general proposition that a cognitive act, in this case the simple act of directing visual attention to the location of a cue, is carried out by a network of anatomically defined areas. The network in this case is a vertical one in the sense that it includes both areas of the cerebral cortex and areas underneath the cortex in the thalamus and midbrain. The results also suggest that each area included in the network carries out special computations to accomplish a particular mental operation. They imply the existence of a circuit in which the DISENGAGE operation is performed by the posterior parietal lobe, which then passes control to the midbrain so that attention can be shifted to the location of the target. Finally, the thalamus, which has direct input to the pattern recognition ("what?") pathway, appears to be involved in the EN-GAGE operation: it amplifies visual information coming from the target so that the information receives priority in processing. The properties of the individual cells within the parietal lobe, colliculus, and pulvinar suggest that these areas are all involved in attention, and the patient data indicate that lesions to these areas disrupt specific operations. Even this very simple form of attention does not reside at any one location, but is a property of a set of areas working together in a highly orchestrated fashion. More detailed evidence from neuroimaging studies of this and other attentional networks will be presented in Chapter 7.

In this chapter we have seen how cognitive operations can be isolated by measuring their time demands and their competition with similar operations. We examined a strategy for linking these operations to underlying neural systems. Some data already exist from brain-damaged patients to support the idea that mental operations are localized in particular neural areas. We turn now to the contribution of neuroimaging methods, which provide powerful new help in establishing links between mental operations and neural systems, and ultimately between mind and brain.