

THEORIES OF LEARNING

A Comparative Approach

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Memory and Information Processing

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INTRODUCTION

Overview

This chapter is an introduction to an old approach to the study of behavior which has once again become popular after over a century of obscurity. This approach is called *information processing*, and while it certainly has strong implications for the study of memory, it has also been applied to areas such as perception that are beyond the scope of this text. Since there is no single theorist whose work would be completely typical and representative of the information-processing approach to memory, we take a slightly different tack in this chapter and discuss the theoretical efforts of several researchers, instead of highlighting the work of one theorist or one approach.

We will focus on two problem areas of learning which are currently the subject of intense experimental investigation: *memory* and *attention*. According to an information-processing view, which regards the organism as a system composed of several interacting subsystems, these two topics are virtually the opposite sides of the same coin. We cannot study memory without being aware of attention, and vice versa. The theoretical treatments of

both topics frequently share the same terminology and concepts.

We have two main goals in writing this chapter. The first is to acquaint you with the history and some of the models, experiments, and implications associated with the information-processing approach. But we can sample only a tiny fraction of these research efforts, exposing just the tip of the iceberg. Thus, our second goal is more important: to illustrate the logic and unique conceptual framework that underlies current research effort in this area. We shall try to give you the flavor of the approach and some insight into the way information-processing researchers formulate and attack psychological problems related to memory and attention. While we have been careful to refrain from overtly stating that the information-processing approach is necessarily better than the traditional and neotraditional learning theories discussed in other chapters, we certainly hope that after reading this chapter you can see how it is markedly different from them.

Major Issues

Human information processing is not a theory of behavior comparable to some

particular theory of learning. It is a general approach based upon a set of pre-theoretical assumptions accepted by researchers who adopt this viewpoint. The most important assumption is that behavior is determined by the internal flow of information within the organism. Since this flow is never directly observable, the specific techniques and methodologies used to infer the details of this postulated information flow are complex. But this methodological complexity should not be permitted to obscure the goal of this research: to map internal information pathways.

Information-processing models of any process, be it memory or attention, will differ according to how the theorist wishes to specify a hypothetical internal-flow diagram. Many alternate flow diagrams are tenable, with each theorist trying to show how his or her diagram can better explain behavior. Thus a major issue which distinguishes competing models is the number of tiny internal "black boxes" or processing stages assumed in any theoretical treatment.

In memory research, there is currently considerable debate over how many different types of memory subsystems are present within the human. Some researchers believe there are separate sensory storage registers for each input modality (vision, audition, etc.) characterized by a very rapid loss of information. These sensory registers are thought to feed into a short-term memory system that can hold a small amount of information only if an active effort is made to retain its contents. This short-term memory in turn feeds into a long-term memory system with a huge storage capacity where items need not be actively maintained. However, other researchers believe that there is basically only one kind of memory system. According to this al-

ternate view, what has been interpreted as the operation of different memory systems is really only the influence of different kinds of encoding operations.

Even more important than the number of internal stages is the kind of information transformation effected by a stage. The human is regarded as an active processor of information with great flexibility as to how information can be transformed inside the organism. For example, visually presented information is often transformed into a code that is basically acoustic or articulatory in nature; that is, one based on how the information sounds or is produced. Such transformations of information are common in physical systems. A computer transforms small holes in punched cards into electrical impulses. A loudspeaker transforms electrical impulses into air vibrations. The study of information processing can be viewed as the search for the coding and transformation rules used to modify information as it flows through the organism.

Basic Concepts

The basic concept in information processing is the stage or isolable subsystem (Posner, 1978). A precise definition of a stage of processing requires considerable mathematical sophistication (Taylor, 1976; Townsend, 1974) and so is beyond the scope of this chapter. However, we can offer a fuzzy definition: A stage corresponds roughly to one transformation of information. In general, the output of an internal processing stage differs from the input.

Stages can be arranged in many patterns. The simplest pattern occurs when we have a chain of stages, with the output of one stage feeding directly into the input of the next stage. This is called *serial processing* because any particular

stage must wait to do its own transformation until it has received the output from the immediately preceding stage. If several stages can simultaneously have access to the same output, this is called *parallel processing*. Now a stage need not wait for other stages, because all parallel stages can operate on the same information together. Finally, if some processing is serial and some parallel, the resulting model is called *hybrid processing*. While hybrid models are often more general and powerful than either serial or parallel models, they are also far more difficult to analyze and to understand. Most current models are serial or parallel, with serial models having an edge in frequency because most people find them intuitively easier to understand.

However, the division of an information-processing structure into serial and/or parallel processing stages is not enough to specify the behavior of the system. We must also know or assume the "price" each stage charges the system for its operation. This is called allocation of resources or capacity. Most models assume some kind of limitation on the resources available to the organism for processing information; this is another way of stating that the organism cannot process an infinite amount of information in a finite time. So the operation of some particular stage may make it impossible for another stage to fulfill its transformation efficiently, or even at all. Many models assume that stages compete for a limited pool of power, energy, capacity (pick the analogy you prefer), so that every stage cannot always work as quickly or as efficiently as if it were the only processing stage in the system. It is even possible to make serial systems look like parallel systems, and vice versa, by cleverly choosing the right assumptions about capacity.

In summary, to predict the behavior of an organism that is attending or memorizing we must have a model that (1) gives the number and configuration of internal processing stages, and (2) gives the capacity requirements of each stage as well as the total availability of capacity.

HISTORY

The fields of information processing and memory are among the oldest in experimental psychology. Decades before E. L. Thorndike observed cats escaping from puzzleboxes or Pavlov studied the "psychic secretions" produced by dogs, careful studies of information processing and memory were carried out in European laboratories. The work of two men in particular stands out as precursors of those studying cognitive psychology today: Frans Cornelis Donders and Hermann Ebbinghaus.

Beginnings

Frans C. Donders, a Dutch physiologist, was already well known for his research on vision when he turned to the problem of the speed of reaction and what it could tell about how information is processed. Donders (1868/1969) developed three different reaction tasks, which he referred to as A, B, and C reactions. (They are still known by these names.) The Donders A reaction, also called the *simple reaction*, involves a person responding as fast as possible to a single stimulus. In a common experimental situation, a person sits at a table with an electric bulb on it. The person's task is simply to respond as rapidly as possible by pressing a button whenever the light goes on. A naturally occurring case of a simple reaction is stepping on

your brake pedal in response to the sudden flash of the brake lights of the car in front of you. Donders believed that the simple or A reaction time reflects such basic factors as the speed of conduction of the nervous impulse, and thus it can be used as a baseline component in analyzing the more complex reaction tasks.

The more complicated B and C reaction tasks involve persons perceiving more than one stimulus. In the B or *choice reaction* task there is more than one stimulus and more than one response; for example, there may be two bulbs and two buttons. Each stimulus governs one response, so that if the left light comes on the person is to press one button, while if the right light is illuminated the other button is to be pressed. Thus the B reaction involves a choice between two responses based on proper identification of the stimulus. It is similar to the decision to be made at a stoplight where one must decide whether to stop or go, depending on the color of the light.

Donders thought the choice reaction involved two mental operations, identification of the stimulus (which light came on?) and selection or choice of the response (which response do I make?). To estimate the time taken by each of these mental operations, it is also necessary to study a third kind of reaction, the C reaction. The C reaction also involves more than one stimulus, but in this case there is only one response and it is to be performed to only one of the two stimuli. A person seated before two lights who is supposed to press a button only when the left light comes on represents an example of a C reaction. Illumination of the other light would not require a response and should be ignored. An example of a C reaction would be waiting for your number to be called at a takeout

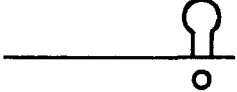

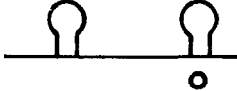
restaurant; you are not supposed to respond until your number is called. Donders believed that the C reaction involves *stimulus identification*, since one has to determine which stimulus is appropriate, but not response selection (choice), since there is only one response.

Once we have measured the times required to perform the A, B, and C reactions, we can compute the amount of time needed for the mental operations of stimulus identification and choice (response selection). The C reaction involves stimulus identification and the baseline time for other processes such as nervous conduction and response execution, while the A reaction simply involves the baseline time. Thus the time required for stimulus identification can be estimated by subtracting the A reaction time from the C reaction time. Similarly, the amount of time required for choice or response selection can be calculated by subtracting the C time from the B (choice) reaction time. This is because the B reaction is considered to have the components of choice (or response selection), stimulus identification, and the baseline, while the C reaction has only the latter two components.

This *subtraction method* devised by Donders (see Figure 10.1) was an ingenious attack on the problem of measuring the stages in information processing. His method was used widely in the late 1800s to study "mental chronometry," as it is called, of other psychological processes. The method fell into disfavor because the estimated times for the mental processes were often quite variable, but also because the structural psychologists who used introspection did not feel as though the simple reaction tasks really contained these separate stages. It was not until the 1960s that reaction-time experiments were reintroduced to the study of infor-

Figure 10.1

Example of the Logic of the Subtraction Method

Reaction	Example	Instruction	Component	Time*
A		Press button when light goes on.	Baseline	300 msec
B		Press left button if left light goes on, right button if right light goes on.	Baseline + Stimulus identification + Response selection (Choice)	800 msec
C		Press button when the right light goes on; when the left light goes on do nothing.	Baseline + Stimulus identification	600 msec

To determine time for stimulus identification:

$$C - A = 600 - 300 = 300 \text{ msec}$$

To determine time for response selection or choice:

$$B - C = 800 - 600 = 200 \text{ msec}$$

* Numbers are hypothetical.

mation processing by Saul Sternberg (1969), Michael Posner (1969) and others.

The first person to study human learning and memory scientifically was Hermann Ebbinghaus. He pioneered new methods of study that have been tremendously influential. His work was published in a brief volume translated as *Memory: A Contribution to Experimental Psychology* (1913/1964). Ebbinghaus served as the only subject in all his experiments, and the materials he devised for memorization are referred to as *nonsense syllables*. He made up 2,300 meaningless syllables that contained a vowel surrounded by two consonants, like DAL and BEP. Ebbinghaus used these rather unnatural materials because he hoped to minimize the influence of prior linguistic

associations in his experiments that would have been present if he had used words, phrases, sentences, or (as he sometimes did) passages of poetry.

Ebbinghaus selected these syllables at random and placed them into lists of varied length. He would read the nonsense syllables in a list to the beat of a metronome until he thought they were almost learned. Then he would attempt to recite the list after looking away. The measure of learning was the amount of time (or the number of recitations) it took to repeat the list perfectly. When the number of recitations (or trials) to mastery of the list is used, the measure of learning is referred to as a *trials to criterion* measure. In attempting later to recall a list, we could measure simply the number of syllables not recalled. But

suppose we attempt to recall a list learned weeks ago, and we cannot produce even a single syllable from the list? Does this mean that there is no memory trace left of that experience? Ebbinghaus did not measure memory or forgetting by the number of syllables that could be recalled at a later time; instead he measured the number of trials (or amount of time) it took for him to *relearn* the list. The memory for the list at the time of relearning could be measured by the *savings* in terms of the fewer number of trials or less time needed to relearn the list than to learn it originally. Thus even if not a single syllable could be recalled from the list, memory for the list could be indirectly measured by the amount of time saved during relearning the list. One of the many interesting things Ebbinghaus discovered was that forgetting is a negatively accelerated function of the time past since learning (i.e., there is great forgetting at first and then the rate slows down). Ebbinghaus applied one of psychology's first mathematical models to account for this forgetting function.

Ebbinghaus pioneered a number of other techniques in the study of memory (see Crowder, 1976, pp. 413–417), and his influence was considerable. Unlike Donders, Ebbinghaus's influence did not wane and remains strong even to the present day, though a number of the specific techniques he invented have been replaced.

Major Theorists

In a field as large as that of information processing and memory it is difficult to name only a handful of major theorists. This section focuses on only some of the people who have influenced cognitive psychology in recent years.

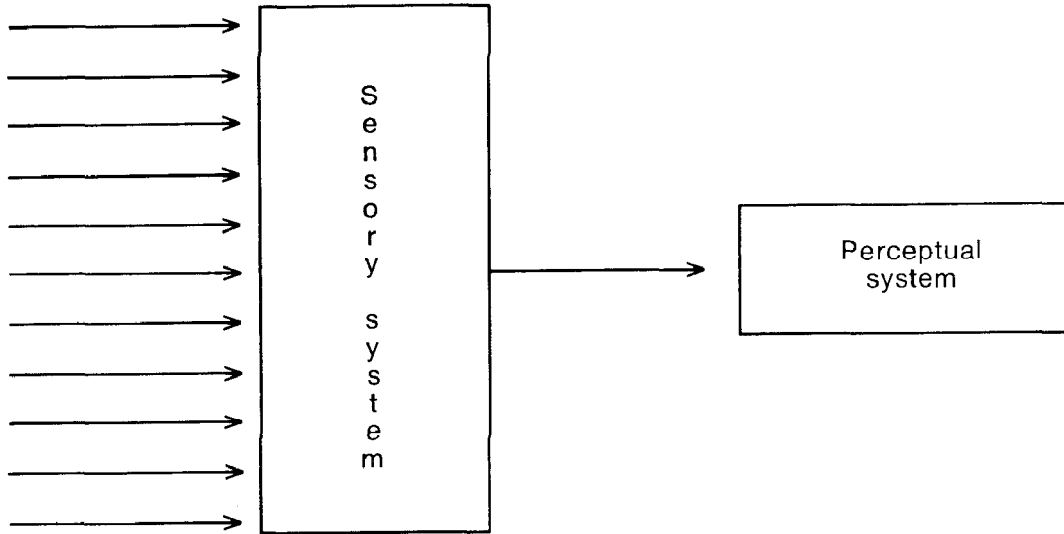
One of the psychologists most respon-

sible for the surge of interest in information processing in the 1950s was Donald E. Broadbent. In 1958 he published *Perception and Communication*, an important book which has inspired much further work. It contained the first information flow diagram, a graph intended to indicate how information passes through an organism in the performance of some task. Broadbent proposed a mechanical model of attention in humans called *filter theory*. Information is believed to be held briefly in a sensory system, and if it is not attended to by the perceptual system it is filtered out or lost (see Figure 10.2). Filter theory has served as a reference point in the study of attention and information processing over the years. Broadbent's views on many of the issues in information processing were updated in *Decision and Stress* (1971).

Saul Sternberg's work in information processing and memory has had great impact in recent years. Sternberg is one of the psychologists most responsible for the rejuvenation of interest in the reaction task and the logic used by Donders in delineating stages in information processing. Sternberg (1969) modified the reaction task to study how information is retrieved from short-term memory. He presented people with a small number of letters or digits to be memorized (e.g., 5, 3, 9, 7). This *positive set* of information was kept small so that individuals could hold it in short-term memory and would not forget it. Then Sternberg presented a test digit that half the time was a member of the positive set (the items presented) and half the time was a member of the *negative set* (the items not presented). The person's task was to respond as rapidly as possible to indicate whether the test item was or was not in the positive set. Since people hardly ever made errors, the interest was in the reaction time to the

Figure 10.2

Information Flow Diagram for Broadbent's Filter Theory of Attention



The information flow diagram represents Broadbent's filter theory of attention. All incoming information is held briefly in a sensory (S) system in parallel (simultaneously) before certain information is selected for further processing by the perceptual (P) system. The perceptual system operates on information serially. Information not processed by the perceptual system is thought to be "filtered out," or not processed beyond the sensory system. (Adapted from Broadbent, 1958, p. 216, Figure S.)

test item. Sternberg discovered that as the size of the positive set increased from two to six items, the time for the person to respond increased at about 40 milliseconds per additional item. Sternberg argued from this and other evidence that people retrieve information in short-term memory by successively scanning or examining each item. Many other findings have been produced by investigators using this paradigm, which has come to be called the *Sternberg paradigm*. Sternberg (1975) has recently reviewed the issues involved in this line of research.

Wendell R. Garner also has made important contributions to the study of information processing. He borrowed concepts from information theory as developed by engineers and applied them successfully to perception and memory. Part

of his work has been concerned with pattern goodness: Good patterns (as measured in several different ways) have great effects on different information-processing tasks. For example, simple patterns are better remembered than more complex ones. Much of Garner's work is summarized in *The Processing of Information and Structure* (1974).

One idea that has attracted much attention over the past 10 years is that there is not a single memory store, but rather two different memory stores with distinct properties (*short-term store* and *long-term store*). This idea was proposed by a number of researchers, but the most complete proposal was that of Richard C. Atkinson and Richard M. Shiffrin (1968). They developed an extended information flow diagram of the kind

first introduced by Broadbent which was meant to model a number of aspects of humans' abilities to process information.

Two psychologists who have greatly influenced the study of memory are Leo Postman and Benton J. Underwood. One of their primary contributions has been the development of the *interference theory of forgetting*. This will be discussed later, but basically the hypothesis is that forgetting of an experience can often be attributed to interference from preceding experiences (*proactive interference*) or succeeding experiences (*retroactive interference*). The interference theory of forgetting is one of the most durable theories of memory, and much of the evidence concerning it has been contributed by Underwood and Postman (for a review, see Postman and Underwood, 1973). Both have also made numerous other contributions.

Endel Tulving has also had a strong influence on the way psychologists think about memory by emphasizing the importance of retrieval processes. Forgetting is not necessarily attributable to a loss or weakening of information as it is stored in memory; instead the difficulty may be in using or retrieving the information. Tulving argues that any experience of remembering must be considered as the product of information from two sources: Information from the memory trace left by the experience and information in the retrieval environment at the time of recall (Tulving, 1974). This point will be explicated later in the chapter.

Allan Paivio has pointed out another important aspect of human memory, the effectiveness of mental imagery as an aid to remembering. There has been a great emphasis in cognitive psychology on the processing of verbal information. This is quite natural, since language is so impor-

tant in human cognition. Paivio's work has served to reintroduce the concept of mental imagery as an important one in understanding human memory and thought. He argues that humans use two primary mental codes to store experience, a spatial/imaginal code and a linguistic code. This idea is referred to as the *dual coding hypothesis*. Much of the work on mental imagery is reviewed in Paivio's *Imagery and Verbal Processes* (1971).

One final theorist (of many possible) to be discussed is W. K. Estes, whose work on mathematical theories is the subject of the preceding chapter. Estes's work has spanned many of the problems in experimental psychology, but in recent years he has turned more to the study of information processing, in particular the problems of perception of letters and words briefly presented (Estes, 1975), the recall of information in the order in which it was presented (serial recall), and probability learning.

Current Status

The study of information processing and memory is one of the most active fields of experimental psychology. After the early and influential work of Donders, Ebbinghaus, and others, the study of information processing and memory for years took a back seat to the study of animal learning and behavior. At about the turn of the century the careful experimental methods of Donders and Ebbinghaus had largely been supplanted by introspective methods. Rather than perform experiments in which behavior was measured, these introspectionists carefully observed their inner mental processes while performing some task and tried to analyze the task into its components on the basis of these reflections. The introspectionists could not agree among them-

selves as to what components occurred in performing even the simplest of tasks, and this unreliability did much to discredit the introspectionist approach.

When John B. Watson introduced the behaviorist arguments against the introspective approach to psychology, the weak tools and results of the introspectionists were no match. The emphasis of psychologists in studying behavior began with the study of processes that could be observed in species other than humans, and thus topics such as information processing and memory were neglected. Watson (1913) argued strongly that psychology did not need mental constructs, and for a long time topics such as imagery, attention, memory, and so forth were not studied. The exciting issues in experimental psychology for the next 40 years revolved mostly around learning in animals.

In the 1950s and 1960s the study of mental processes was reintroduced into psychology. Rather than using introspective techniques, though, psychologists now studied observable behavior. Mental constructs were reintroduced into psychology, but only with several different lines of firm behavioral evidence to back them up (Garner, Hake, & Ericksen, 1956). This new approach to studying the higher mental processes has been termed *neomentalem* by Paivio (1975). Today the study of the higher mental processes forms the field of cognitive psychology, and it has captured the excitement and fervor that was reserved for other issues only a few decades ago.

Other Theories

The study of information processing and memory is not a theory in any real sense. Rather, these are topic areas about which there are many theories. Thus it

makes little sense to contrast this approach with that of the other theories discussed in this book. These other theories actually are distinct theories that address the same content problems from different viewpoints. The approaches discussed in this chapter by and large address different problems from those of the other chapters. Most of the theories reviewed in the other chapters have not been developed to account for the kinds of problems and situations involved in the study of information processing and memory. Similarly, the theoretical viewpoints of this chapter have not usually been extended to cover the kinds of experimental situations considered elsewhere in this book.

PROPOSITIONS

1. *Information flow is the basis for behavior.*

The essence of the information-processing approach is a dominant concern for the flow of information inside the organism. According to this viewpoint, psychology must not only be able to duplicate and control behavior but must also duplicate the detailed processing of information that is hidden. We think of the human as a very complex machine and try to discover what happens inside this "black box." It is not enough to duplicate behavior: A woman singing and a tape recording with a certain brand of tape might both be able to shatter a slender wineglass, but no one would claim that this duplication of behavior demonstrates that the woman and the tape recorder both operate the same way.

Information-processing theorists sometimes represent the human cognitive system as a series of boxes representing information stores and processes that send

information back and forth. Each box may represent one kind of information transformation that goes on inside your head. As we discover more about psychology, the level of detail represented in each box becomes finer. These smaller boxes are often called *stages* of information processing. A typical box or stage would be the one that represents the encoding of signals. When you see a printed word, you may transform this visual information into an acoustic or articulatory code based upon the sound of the word or how it is pronounced. Subsequent processing is based upon this code and not upon the visual shape of the original stimulus; indeed, you may be unable to report about the original stimulus—was it in upper or lower case, how tall were the letters, was it script or block lettered, and so on? It is possible to take even this small unit of information processing—that is, the stage that transforms visual input—and break it down into yet smaller stages that process individual letters or even individual strokes within letters. But no matter how many stages are discussed, the logic of the analysis is the same. The attempt is to break down a complex process into its components and to show how these components interact.

Cognitive psychologists often attempt to map the internal information flow by using technologies borrowed from disciplines like engineering and computer science. However, engineers can often get inside their black boxes to insert meters. Psychologists are far less fortunate in this regard. While psychophysiological techniques may offer hope for the distant future, right now we cannot gain direct entry into the processing flow within the organism. So we are forced to infer alternate flows and then to determine which postulated flows are most consistent with observed behavior. There are times when

we discover that two alternate flowcharts are equivalent in terms of predicted behavior, even though they may look quite different at first glance. Thus information-processing psychologists usually concentrate on testing classes of models rather than specific details of one model (Broadbent, 1971, Chap. 1). We may decide, for example, that the class of models postulating some filter mechanism early in the flow of information is not as good as the class that puts the filter nearer the end of the flow of information. Or we may compare the class of models which state that stages can work only one at a time (*serial models*) to the class which allows several stages to operate on the same information simultaneously (*parallel models*). This approach may get a lot more mileage out of an experiment than does the hypothetico-deductive method, in which only one specific theory is tested.

In the traditional approach, in which postulates of one theory were tested, theories and experiments got so complicated they were hard to validate. As more and more postulates were added to a theory, it became awkward to test. And simple tests, while consistent with many hypothetico-deductive theories, were often also consistent with simpler explanations that were not considered. Comparing classes of models, rather than testing one theory at a time, makes better use of experimental effort.

2. *Stimuli that did not occur can exert control over behavior.*

Traditional learning theories, such as Clark Hull's, maintain that behavior is controlled on any given trial by the stimulus present on that trial. This seems obvious, and it is hard to imagine how a stimulus not present can alter behavior.

But information-processing theorists have shown that the set of possible stimuli—that is, all those stimuli that might have occurred—is at least as important as the particular stimulus that did occur.

This can be demonstrated rather easily in a choice reaction-time experiment. It is well known that reaction time increases as a function of the amount of *information* in a stimulus set. The unit of information is the bit: One bit is the amount of information gained by tossing a fair coin that can come up either heads or tails. Tossing two coins has four possible outcomes (HH, HT, TH, TT) and two bits of information. Each time we double the number of equiprobable possible outcomes we gain one bit of information. Choice reaction time is a linear function of information; that is, every time the number of alternatives that must be examined is doubled, reaction time is increased by a constant amount. Let us illustrate this finding. If we have two lights and two response keys we can easily measure choice reaction time: the time between the onset of one of the lights and the depression of the appropriate response key. Now let us add two more lights and keys to the set and again turn on the very same light as before. Now reaction time will be increased. Even though the physical stimulus is the same—say the light on the left end of the row of lights—behavior has changed, as indicated by a change in reaction time. Adding two more S-R alternatives has increased reaction time, even though those alternatives did not occur on this particular trial. However, they could have occurred. Choice reaction time is controlled by the set of possible alternatives rather than the particular stimulus that occurred.

The concept of expectancy has been resisted by many traditional learning theorists. Yet it provides a relatively simple

explanation of these choice reaction-time data. Behavior is influenced by the person expecting more alternatives. Expectancy can be manipulated by priming—that is, presenting an initial stimulus that tells the probability of a following stimulus. For example, the following stimulus might be the letter A or the letter B. The priming stimulus could tell the individual that there is an 80% chance that B will be the next stimulus. If a B actually occurs, reaction time is faster than a control condition in which no priming stimulus was given. Of course, if an A occurs, reaction time is slowed down. Expecting a stimulus speeds up reaction time (Posner, 1978).

It would be unfair to claim that these data could not be explained at all by learning theorists. If complicated assumptions about generalization gradients are made, it might be possible to generate accurate predictions. However, this would be cumbersome at best, and the same predictions can be more readily generated from information-processing assumptions.

3. *The human has a limited capacity for processing information.*

This has been the most fruitful proposition of information-processing approaches to behavior. It was originally derived from a model of a telephone communication system devised by Claude Shannon and Warren Weaver (1949), mathematicians at Bell Telephone Laboratories who invented information theory. A telephone cable can only carry so many conversations at a single time; this limit is its capacity to transmit information. Important new insights about human behavior have been gained by thinking of the human as a limited-capacity channel, similar in principle to a telephone line.

The research areas of memory and at-

attention have benefited most from this view of the human's limited capabilities. The important distinction between short- and long-term memory systems is based in part upon differences of capacity. Long-term memory has an almost unlimited capacity for information, whereas short-term memory can only hold from three to six items at one time. Attention is a broad topic which covers both humans' ability to focus on one subset of stimuli while ignoring others and their inability to do several things simultaneously.

Although the idea of a limited-capacity human was the work of many psychologists, the man who was its most articulate advocate was Donald Broadbent (see the History section). His information-flow conception of the human (Broadbent, 1958, 1971) stresses two important mechanisms relevant to attention. The most important, of course, is the limited-capacity channel itself. This has occasionally been misinterpreted to mean that the human can do only one thing at a time. This is false. The model states that the human can process a limited amount of information per unit of time; that is, humans are limited by their *rate* of information processing. This limit is called their channel capacity and is measured in bits/sec. If the total demands of a set of tasks are less than channel capacity, all the component tasks will be performed without impairment. If the total exceeds available capacity, performance on some task(s) will suffer. In the limiting case the set of tasks reduces to only one, but the prediction of the limited-capacity model remains the same. If a single task exceeds channel capacity it will be performed imperfectly; if channel capacity exceeds the demands of a single task no performance decrement will be observed.

The second most important mechanism proposed by Broadbent is a filter that

protects the limited-capacity channel from excessive stimulation. Only information that successfully passes the filter is allowed to enter the limited-capacity channel. So the filter can be regarded as an early stage of perceptual processing. While there has been some controversy about the specifics of filter operation (Broadbent, 1971), the basic conclusion about human selectivity is still correct. However, this selectivity may be accomplished at other stages in addition to, or in place of, an early-selection filter.

The great amount of research engendered by the limited-capacity model has resulted in the discovery of a few situations where the human can do more things simultaneously than the model predicts. Although the limited-channel model remains an excellent first approximation, there is now some doubt about many of its specific details. Other models stressing parallel channels and variable capacity mechanisms are challenging Broadbent's views. This in no way diminishes the importance of his model, since it was responsible for getting many learning theorists and experimentalists to think in terms of information flow in the first place. But it is clear that the notion of the human as a limited-capacity processor, while correct in an overall sense, marks the start of a new problem area for psychology rather than the solution.

4. *Mental events can be inferred from chronometric analysis.*

This proposition is often taken as evidence that psychology today is asking the same questions it did over a century ago. The notion of a mental event was the basis for an entire school of psychology based upon introspection. The structural psychologists (such as Edward Titchener) tried to break down mental events into component parts on the basis of analysis

of sensations. The information-processing analysis of mental events is quite different, since it is based on analyzing the event in terms of behavioral effects. It is historically interesting that one major tool used for this analysis, measurement of reaction time, was available over 100 years ago but was then rejected, since it could not be corroborated by introspective reports. (See discussion of Donders in the History section.)

Modern chronometric analysis takes up where F. C. Donders left off, although he deserves the credit for demonstrating the utility of reaction time as a dependent variable. Chronometric analysis is defined as the use of reaction-time data to measure mental events; indeed, some researchers go even further and claim that if used properly, accuracy measures also meet the demands of chronometric logic (Posner, 1978). While Donders tried to determine the duration of mental events such as selection and identification, current chronometric analysis is satisfied to identify subunits or stages of mental activity without specifying their duration. The mathematics and details of this technology cannot be covered here (see Sternberg, 1969; Taylor, 1976), but the logic can be sketched.

The method of *additive factors* takes a total reaction time and decomposes it into successive stages of internal information flow. Independent variables or factors are manipulated to alter durations of mental events. The relationships between factors and stages are inferred from analysis of variance and related statistics. Factors which interact influence the same stage, while factors which are additive—that is, fail to interact—influence different processing stages. So, the additive-factors method allows us to discover the number of processing stages associated with some set of independent

variables. This is how measurements of reaction time allow us to infer the existence of mental events.

5. *Memory for a stimulus depends on the complexity of the mental operations applied to it when it was initially processed.*

It has been proposed (Craik & Lockhart, 1972) that memory for an experience is a byproduct of the processing the stimulus receives as it is perceived. Perception is believed to proceed through a series of processing stages from relatively “shallow” sensory analyses through more complex, “deeper” analyses which involve higher cognitive structures, such as long-term memory. Craik and Lockhart proposed that information can be processed to different *levels* and that the greater the depth of initial perceptual processing, the more likely is later recall of the experience. This general viewpoint is referred to as the *levels (or depth) of processing framework*, and it has proved a popular and useful view in interpreting memory phenomena.

Later in this chapter we consider specific experiments that can be interpreted within the levels-of-processing framework, but let us now consider a common example. Suppose you have had two years of Spanish in high school, and one day while riding around in your car you tune to a Spanish language radio station on which an announcer is talking. You decide to try your best to understand what is being said. However, you soon discover that for many words and passages you cannot make out what is being said, or even where the words begin and end, because the announcer is speaking rapidly and using words to which you are not accustomed. These words and passages are, of course, receiving some oblig-

atory perceptual analysis as you try to understand them, simply because they are being processed by your auditory system. However, this analysis qualifies only as shallow processing, since you are not able to derive the segmentation between the words or their meaning. For other words and phrases you can probably make out the different words and can sound out and repeat them, but you still are not able to understand what they mean. You have thus processed the information beyond a sensory level of coding to the way the words sound, but more complex semantic processing involving the meaning of the message is still lacking. Finally, for some words and phrases you are able to recognize the words and understand what they mean, thus achieving deeper levels of processing of the material.

Now suppose you were asked to recall what you had heard an hour after you listened to the Spanish radio broadcast. What would you be able to recall? You would probably recall almost nothing about those parts that you did not understand (processed only to a shallow level), perhaps a few of the words that you could sound out but did not know the meaning of, and probably a great deal of those parts that you were able to understand (that were processed to a deep level). Many experiments interpreted in the levels-of-processing framework follow the same logic as this example: Individuals given the same stimuli are required to perform different tasks on the material that force processing to different levels, and the effect of this variable on later recall or recognition is observed.

The levels-of-processing framework has undergone considerable modification from the ideas just presented (e.g., Craik & Tulving, 1975), and it has also attracted critics (e.g., Baddeley, 1978; Nelson, 1977). It may be better to formu-

late the important variable determining recall as "complexity of mental operations performed on the stimulus" rather than the level of processing. Kollers (1973) found that people who had read sentences presented upside down recognized them better later than people who had read the same sentences presented in normal typography! Reading inverted text certainly involves more complicated mental operations than reading normal text, but it probably does not involve a deeper level of processing. Thus complexity of mental operations is emphasized in this proposition, rather than level of processing. Another complex mental operation that improves memory is dealt with in the next proposition.

6. *Forming images of material to be remembered greatly aids later recall.*

People have been aware of the validity of this proposition to a greater or lesser degree for thousands of years. Greek and Roman rhetoricians admonished their students to remember the points in a speech they were to make by forming images of the points and locating them at different places along a familiar path. When they were to give the speech they could retrieve the successive points they wished to make by mentally walking down the path and "looking" to see images of the different points. This technique is known as the *method of loci* and is only one of numerous *mnemonic devices*, or aids to memory, that have been devised (see Yates, 1966). Almost all these memory aids are based on use of mental imagery, as are memory systems suggested in modern books such as *The Memory Book*, by Harry Lorayne and Jerry Lucas (1974).

The experimental methods of modern

psychology have confirmed this belief that imagery aids memory. For example, Bower (1972) found much better recall of word pairs for persons told to form images of the referents of the pairs than for persons simply told to repeat or rehearse the pairs. Paivio (1971) reported similar results and also showed that words rated high in image-evoking value (e.g., blood, table, rhinoceros) are better recalled and recognized than low-imagery words (e.g., truth, beauty, democracy), even when the words are matched on other qualities such as their length or frequency of occurrence in English.

The formation of images to aid recall may be seen as a corollary of the preceding proposition, that complex mental processing applied to an event improves memory for it. However, it has been argued on numerous grounds by Paivio and others that the imaginal system represents a different code for representing experience than linguistic codes. Thus image formation may not simply represent a more complex mental operation but rather a code in a qualitatively different cognitive system. The debate on this issue continues (e.g., Anderson, 1978; Kosslyn & Pomerantz, 1977; Pylyshyn, 1973). The usefulness of mnemonic devices is considered further below in the Implications section.

7. *Memory for an event is a product of information from two sources: the memory trace laid down by the event and the cues in the retrieval environment when recall is attempted.*

The two preceding propositions have focused on how information is stored, with the assumption being that so long as information is stored well, it will be recalled. But adequate storage of informa-

tion is only half the story; without appropriate retrieval information to complement the information in storage, one will not be able to recall an event. The importance of retrieval for a theory of memory can be illustrated in a number of ways. You have probably often had the experience of trying to recall something, failing in your initial attempt, and then putting the matter aside for a time. Later you may try again, with seemingly no new information at hand, and succeed. Obviously the information was stored in memory and your initial failure to recall it was due to a retrieval failure, since you were able to retrieve it on the second try. Psychologists studying simple events such as the recall of a collection of pictures or words in a list have observed the same phenomenon. Often when people are given repeated tests for the same information or are given one test over a prolonged period of time, information that people could not recall immediately is eventually recalled (Erdelyi & Becker, 1974; Roediger & Thorpe, 1978).

A more direct way to demonstrate the importance of retrieval in the memory process is to manipulate the nature of the retrieval environment by providing the rememberer with different sorts of retrieval cues. In one well-known experiment, Tulving and Pearlstone (1966) presented high school students with lists of words to remember. The words were members of common categories and were presented in appropriate groups, for example: Birds—*Dove, Sparrow*; Furniture—*Couch, Bed*; Colors—*Yellow, Blue*, and so forth. The participants were told that they need remember only the words, not the category names, for later recall. We will consider only two conditions, in both of which people heard 48 words, two words in each of 24 categories. Individuals in the two conditions heard the

words under exactly the same conditions of presentation, so we can assume that they stored roughly the same amount and kind of information about the words. The only difference between the two conditions was at recall. Individuals in one condition were simply asked to recall the words in any order they wished (free recall). Those in the other condition were also told to recall the words in any order, but in addition they were given the category names as retrieval cues.

The free-recall students recalled an average of 18.8 words; without further information, we might assume that information about the other 30 or so words was not stored well enough for later recall. However, students given the category names as retrieval cues recalled 35.9 words, or almost twice as many. Since both groups of students stored the information under the same conditions, it is apparent that the difference between the two was due to the different conditions operating at retrieval. The retrieval cues allowed people to recall many words that they could not recall unaided. To use Tulving and Pearlstone's terms, there is more information *available* in the memory store than is *accessible* under conditions of free recall.

It is obvious from the comparison of conditions in the Tulving and Pearlstone (1966) experiment that retrieval cues can be powerful aids in determining recall. But what determines whether or not a retrieval cue will be effective?

8. *The effectiveness of retrieval cues depends on their relation to the nature of the stored information.*

The effectiveness of a retrieval cue depends on the degree to which the cue reinstates the original encoding or interpretation of the to-be-remembered ex-

perience. Suppose you were asked to recall as many experiences as possible that happened to you while you were in elementary school. You could probably recall a good number, but after a while you might feel as though you had recalled as many as possible. Suppose you were then taken to the school and allowed to wander the halls freely for a time. You would probably discover that you could now recall many more of your grade school experiences. Presumably the school environment served to remind you of additional experiences, since it helped re-create the original context in which they occurred.

The idea that the effectiveness of retrieval cues depends on their reinstating the original interpretation (or encoding) of the experience has been called the *encoding specificity hypothesis* or *principle* (Tulving & Thomson, 1973). It bears a close formal resemblance to the idea of stimulus generalization (discussed in Chapter 4 in this book), but demonstrating encoding specificity effects is tricky, since it is assumed that the same overt or nominal stimulus can be encoded in different ways. The visible or public characteristics of an event that may seem important to the experimenter may not be the aspects that the subject encodes. Thus the experimenter cannot simply assume that manipulations of the environment along the dimensions that he or she regards as important will determine performance, because individuals may have encoded the information along *some other, less obvious, dimension*.

Let us consider an example. Suppose you study a long list of words, one of which is *Violet*. If *violet* follows the words *daisy*, *tulip*, and *zinnia* in the list, you are likely to encode it as a flower. Later on when you are tested you will be more likely to recall *violet* if you are

given the retrieval cue *flowers* than if you are simply left on your own to try to recall the words with no cues, in any order (a free-recall memory test). Suppose at the time you were tested you were given the retrieval cues *girls' names*. Would this aid recall of *violet*? Probably not, since *violet* was encoded originally in the context of other flowers rather than in the context of girls' names. If *violet* had been presented along with *Linda*, *Susan*, and *Barbara* at the time the list was studied, then *girls' names* would serve as an effective retrieval cue, but *flowers* (or *colors*) would not. The basic point is that the "same" word (at least in its overt stimulus properties) can be encoded in different ways, and how the word is encoded determines what kinds of cues will be effective in later allowing the rememberer access to the trace of the word.

The encoding specificity principle generalizes to many other memory situations than those employing words that have more than one meaning. There are a great number of variations that reveal the same type of effect we have just illustrated. The same nominal event can often be embedded in two different contexts, and then two different sorts of cues can be shown to be differentially effective, depending on the original encoding context. One of the more interesting cases of such a mechanism is called *state-dependent retrieval* (Eich, 1977). People who study material while under the influence of a drug that acts on the central nervous system (e.g., alcohol or marijuana) can later recall more information learned during that time if they are given the drug again than if they are sober. The cognitive state at the time of study determines how the information is encoded, and how the information is encoded de-

termines the effectiveness of retrieval routes to the information.

9. *Events occurring prior to or after events that are to be remembered interfere with recall of the to-be-remembered events.*

Two types of interference may be delineated: proactive and retroactive interference. Both can be illustrated by reference to a simple experiment that has an experimental group and a control group. In the case of *proactive interference*, the experimental group first learns some material (call it List A), then learns another set of material (List B), and finally is tested for recall of List B. The control group performs some unrelated activity for a time equivalent to that in which the experimental group learned List A, then they learn List B and are tested on it later. The typical finding is that B is recalled less well by the experimental group than the control. The list learned by the experimental group prior to B is said to interfere proactively with retention of B. Proactive interference is thus the inhibiting effect that the learning of some prior events exerts on retention of events learned later.

In a *retroactive interference* paradigm the experimental group again learns List A and then List B. However, in this case the experimental group is asked to recall A. The control group learns A and then performs some relatively neutral interpolated activity until tested for A. Again the typical finding is that recall of A is worse when B has been learned after A (the experimental condition) than when there has been no learning of similar material afterward (the control condition). The second list is said to provide retroactive interference for the first list.

It should be noted that the terms *proactive* and *retroactive interference* are descriptive terms, not theoretical ones. That is, they merely describe the outcome of typical experimental arrangements, they do not explain why it occurs. The facts of retroactive and proactive interference are basic ones, and any theory of memory that pretends to be at all general must explain the facts associated with these phenomena. Most of the early explanatory attempts dealt more with the phenomenon of retroactive interference, to the relative neglect of proactive interference. J. A. McGeoch (1942) argued that retroactive interference occurs because of *response competition* at retrieval. That is, one set of responses (those in List B) compete at retrieval with those from the appropriate list (List A), so that the rememberer fails to recall the desired items because of an unwanted intrusion in recall of the items from the other list. Thus the basic idea is that forgetting is not a loss in the availability of information from memory but is a blockage at retrieval caused by competing responses. This response competition interpretation also accounts for the effects of proactive interference, which is important; Benton Underwood showed in a classic paper (1957) that a great deal of forgetting can be attributed to proactive interference.

Arthur Melton and Jeffrey Irwin (1940) reported results that they interpreted as indicating another factor besides response competition is necessary to account for retroactive interference. They speculated that this factor is *unlearning*, which has been likened to the extinction of a conditioned response. While individuals learned the second list, first-list responses were thought to be unlearned and were therefore not well

recalled after second-list learning. Later first-list responses were thought to recover in strength, just as extinguished responses in other organisms exhibit spontaneous recovery after a delay. Evidence provided in numerous experiments over the course of some 20 years following Melton and Irwin's paper seems to bear out, by and large, their interpretation. Thus in what came to be the accepted interpretation of interference phenomena, called *two-factor theory* or simply the *interference theory of forgetting*, both the factors of response competition and unlearning-recovery were thought to play a role. In more recent years other ideas have been put forward to account for interference phenomena and to challenge two-factor theory, but as yet none has gained general acceptance (see Postman & Underwood, 1973).

RESEARCH

Methodologies

Attention. The basic methodology in studies of attention requires imposing some information overload on the human. This technique is borrowed from engineering, where it is quite common: For example, metal alloys are placed in large hydraulic presses and then placed under great pressure until they fail. Of course, a gentler method of imposing overload is mandated when humans are the objects of study.

Since channel capacity is based upon rate of information flow, there are two ways to impose excess information load. First, we can increase the rate at which successive stimuli impinge on the organism. As the time between successive stimuli decreases it becomes progressively more difficult for the organism to keep

up with the incoming information flow. Second, we can increase the number of things the organism is required to do at the same time. Even though the component tasks may be well within available channel capacity, the combination of tasks can easily exceed it.

These two general categories of overload can be broken down into many more specific techniques called *paradigms*. While each paradigm has been originated in hopes of answering some general question about attention, there has been an unfortunate tendency in both memory and information-processing research for these paradigms to become autonomous. Thus, we become so concerned with the paradigm itself that we sometimes forget why it was devised in the first place—a clear case of not seeing the forest because the trees are in the way. In this section we will explain some typical paradigms: how they got started, what we know now, and some representative experiments.

Memory. Contemporary studies of memory usually employ experimental techniques that, as in the study of information processing, overload the cognitive system. However, rather than overload parts of the system responsible for the initial perception of information in the first few hundred milliseconds after it is presented, stimuli in memory experiments are typically presented under fairly leisurely conditions, to ensure that the perception of the stimuli is accurate. The memory system is overloaded by presenting more information than can be perfectly recalled or recognized so that the experimenter can examine the effect of independent variables on the number (or proportion) of items correctly recalled or recognized. It is less common for time measures to be used in memory than information processing, but some recent studies have measured recognition

speed (Sternberg, 1966) and speed of recall (Roediger, Stollon, & Tulving, 1977).

There are numerous ways to measure memory, but all involve some form of recall or recognition. In tests of recall, people are required to reproduce material to which they have been exposed; while in recognition tests, material is presented to people and they are required to judge whether or not they have seen it previously. It is common to distinguish among three types of recall tests: serial recall, free recall, and paired-associate recall. In a *serial recall* task people are required to recall information in the same order as presented to them, while in *free recall* the order of information is irrelevant. People are free to recall the information in any order they want. In *paired-associate recall* individuals are presented with pairs of items, such as *cracker-balloon*, and at recall they are usually given the left-hand member of the pair (*cracker*, called the stimulus) and asked to recall the right-hand member, the response. There are other types of cued recall tests besides paired-associate recall where people are given cues for material they are to remember. For example, following presentation of sentences, people may be given the subjects of the sentences and asked to recall the objects. In other cases they may be given associative cues that were not in the set of study material to determine whether or not the cue will aid recall (e.g., *table* may be provided as a cue for *chair*, which appeared in the list).

Recognition tests are generally of two types. *Forced-choice* recognition tests are multiple-choice tests. Several alternatives are presented, and the person's task is to select the correct one. In yes/no tests people are given the original material they studied mixed in with a number of

new but generally similar alternatives. They examine each alternative and decide *yes* or *no* as to whether or not it was a member of the set they were to remember. Forced-choice recognition tests are generally preferred to *yes/no* tests because the problem of guessing is more easily taken into account.

Recall and recognition tests are usually seen as tapping quite different aspects of performance. However, recently some researchers have viewed the recognition situation as essentially a cued recall situation where the "cues" are very strong. (They are called *copy cues*, since they are copies of the original material that was experienced.) In this section we will illustrate some of the methods that have been briefly outlined here with experimental examples on several different topics.

Animal Studies

Studies of information processing in organisms other than humans are rare, although many of the concepts applied in the study of animal learning resemble those applied to information processing in humans (see Sutherland & Mackintosh, 1971). The parallels between the study of animal and human memory are more direct, although a good part of the research with lower organisms is concerned with discovering the neurophysiological underpinnings of memory.

One issue that has been hotly investigated is the nature of a consolidation process that is thought to be necessary for learning. Consolidation generally refers to perseverating neural activity or time-dependent biochemical changes of some other sort that promote learning after some experience. If some abrupt physiological insult occurs to the organism shortly after some experience, the neural

trace may not consolidate, and thus the experience will be forgotten. The forgetting exhibited by people who have had concussions from an accident for events that occurred just prior to the accident may be attributed to a failure of consolidation. Forgetting of prior events in such situations is referred to as *retrograde amnesia*.

Consolidation processes have been studied in animal memory for some years. A typical procedure is to train mice or some other animals on a passive avoidance task. A mouse is placed on a platform, and if it steps off it receives a shock from an electrified grid. Thus the animal learns to avoid the shock by not making a response and by remaining on the platform. In experiments investigating consolidation, animals are given a single trial in a passive avoidance situation and then are given electroconvulsive shock (ECS) from electrodes attached to their ears, at varying intervals after stepping down off the platform. If the shock were to disrupt the consolidation process, the animals should show poor retention of the response when tested later, relative to controls who were not given the electroconvulsive shock. Further, the forgetting should be greater the sooner the ECS occurs after the animal steps down. These are exactly the findings that have been reported (see McGaugh & Dawson, 1971, for a review).

It is also possible to produce such retrograde amnesia by giving an animal certain drugs soon after learning some experience. In fact, if a learning trial is simply followed by a relatively innocuous but unexpected or surprising event, animals will show forgetting of the preceding experience (Wagner, Rudy, & Whitlow, 1973). Thus, as with humans (e.g., Tulving, 1969), retrograde amnesia can be produced in animals by fol-

lowing an event to be learned with an unusual or surprising stimulus.

It was originally thought that the retrograde amnesia produced by ECS indicates a failure of learning or storage on the part of the organism. However, some more recent work has indicated that the memories which seem "lost" after ECS can sometimes be recovered with the passage of time or by providing a reminder stimulus, such as the foot shock that animals received when stepping down from the platform (Miller & Springer, 1973). Similarly, following concussions people often gradually recover their forgotten memories. What this recovery may indicate is that the amnesia produced by ECS may not be due to a disruption in the process of storing information through consolidation, but may rather be due to a disruption in retrieval of stored information. This general viewpoint represents a convergence between researchers studying human and animal memory; forgetting appears to be attributable in many situations to retrieval failures rather than failures in learning and storage (see Spear, 1978, for a detailed review of these issues in studies of both animal and human memory).

Human Studies

Dichotic Listening. In this paradigm, two different messages are presented, one to each ear. This is similar to listening to stereophonic high fidelity, with the important exception that the two messages in dichotic listening are independent, whereas they are closely related in stereophonic listening. The messages themselves can be almost anything: words, sentences, digits, musical tones, and so on. This task requires the listener to follow the information presented in one ear,

despite the simultaneous input of different information in the other ear.

At first, this may seem a strange task that has but little relationship to anything outside the laboratory. After all, people seldom go about with earphones on their heads tuned to two different stations. But this task was originally developed because of observations outside the laboratory and before formal models of attention were well advanced. Broadbent (1954) started his research on dichotic listening because he was concerned with a very practical problem: How could air traffic controllers monitor conversations with several pilots at the same time? When all the messages came over the same loudspeaker it was quite difficult for the controller to hear only one pilot without confusion. If you have never been an air traffic controller you may find it hard to appreciate this difficulty. However, all of us have been at noisy parties where the same attentional effect occurs. Imagine yourself at a party, engrossed in conversation with an attractive member of the opposite sex. Despite the loud background noises—record players, people talking, ice rattling in glasses—you can still focus in on your own conversation, at least enough for successful communication. You have been able to select a single message out of the set of all messages that could be heard at the party. This is precisely the same task faced by an air traffic controller: selecting one message from an ensemble.

Broadbent (1958) solved this practical problem by using more than one loudspeaker, so that each pilot was associated with a specific location. This made it much easier for the air traffic controller who had to attend to a specific pilot, because he could locate the pilot's voice in a particular location. But Broadbent did not stop there. Instead, he went on to ask

why that solution proved to be helpful. Broadbent postulated a hypothetical filter device that removes unwanted messages. How did the filter work? Basically, it selected some incoming channel on the basis of a physical characteristic of the stimuli, like its location in space or the frequency characteristics of the voice. Several predictions of this model have been made and tested.

First, the more similar the characteristics or channels of two or more messages, the harder it should be to filter out the unwanted ones. So, for example, if one voice is male (with low auditory frequencies) and the other is female (with high frequencies) it should be easier to follow one and reject the other, compared with the same voice (with a different message of course) in each ear. This prediction was supported by experimental results.

Other predictions fared less well. In the most common variant of the dichotic listening paradigm, listeners must repeat aloud or *shadow* one message: This assures the experimenter that the listener is following instructions and attending to the designated message. According to the filter model, then, information about the other channel should be filtered out and lost. But some experiments (Gray & Wedderburn, 1960) found that the filter "leaked" because unattended information could be retained if it was important; for example, if your name occurred in the unattended channel you would notice it at least part of the time. The filter model predicts you would never notice it. There were some attempts to explain this within the filter model by allowing the filter to switch rapidly back and forth between two channels, but these efforts ultimately were unsuccessful.

A series of dichotic listening studies carried out by Treisman (1960, 1969;

Treisman & Fearnley, 1971; Treisman & Geffen, 1967) did much to convince researchers that the filter was really an attenuator: that is, instead of completely eliminating rejected channels all it did was to weaken them. We shall examine one typical study. In a shadowing experiment, Treisman (1960) presented a passage from ordinary text to one ear and word sequences based upon statistical approximations to English on the other. These sequences were meaningless combinations of words. Individuals were instructed to shadow the ear containing prose. However, during the experiment the two messages would switch so that individuals were then shadowing the approximations to English. At the time of switching, intrusions from the unattended ear occurred. This indicates that the content of the unattended ear was available and that contextual cues such as the constraints of English language could override the filter mechanism. So the filter was better regarded as an attenuator rather than a switch.

Treisman's model, like Broadbent's, is part of a class of *early-selection models*, so called because the attenuator operates on an internal representation of the stimulus before making contact with memory. Unattended or weakened aspects of incoming stimuli are dropped early in the processing chain, so that selectivity begins immediately. The early-selection models compete with a class of models that assume all incoming information makes contact with memory. These *late-selection models* (Norman, 1968) easily explain the retention of information from unattended channels on the grounds that all information, attended and unattended, receives the same initial processing. In a shadowing task, the auditory repetition of the attended message is assumed to interfere with retention of other information,

in much the same manner as interference causes memory decrements in learning tasks. It is too early to state which view of attention is correct; indeed, recent research has tended to blend aspects of both early- and late-selection models.

Time-sharing. Like the dichotic listening task, the time-sharing paradigm overloads the human by demanding simultaneous performance of two tasks. However, the overload is even greater than in dichotic listening because both component tasks must be performed, whereas in dichotic listening one channel usually can be ignored. Early studies of time-sharing aimed at testing the limited-capacity model generally were in agreement with its predictions. A typical study—which incidentally won an award for the best doctoral dissertation in experimental psychology that year—was conducted by Louis Herman (1965), who combined a tracking task with an auditory discrimination task. In a tracking task the subject is required to follow (or track) a moving target. Each component task had two levels of difficulty. When two difficult tasks were combined, thus exceeding channel capacity, performance suffered far more than with a combination of two easy tasks.

Quite recently, experimenters have been able to find some task combinations where difficult tasks can be performed together without the decrement predicted by the limited-capacity model. While the first of these findings was greeted with astonishment, if not outright disbelief—much like the finding in chemistry that the noble inert elements could sustain chemical reactions—there is now enough evidence to show clearly that in certain time-sharing situations the limited-capacity model is incorrect. Allport, Antonis, and Reynolds (1972) used component tasks of shadowing and sight-reading music. Sight-reading performance

was unchanged when shadowing was not required versus concurrently required. One might be tempted to dismiss this result as due to insufficient difficulty of the component tasks—that is, the capacity requirements of shadowing and sight-reading together were still within the capacity of the channel. However, Allport et al. were careful to use two levels of difficulty for sight-reading as well as for shadowing, so that this explanation of their results is unlikely. They proposed a multiple-channel model to explain their findings. Several independent processors work side by side in this model. This is an important change because it permits parallel processing. The limited-capacity channel of Broadbent was a strictly serial device, with one operation having to be completed before the next could begin.

While it is not yet clear that the whole of the channel can be duplicated in parallel, at least some parallel processing is required to explain human time-sharing behavior. Indeed, a compromise hybrid model which permits some information flow at early stages to proceed in parallel until a serial bottleneck is reached later in response-processing stages has recently been proposed (Kantowitz & Knight, 1976b).

Psychological Refractory Period. In the psychological refractory period (PRP) paradigm, the human is overloaded by presenting two stimuli in close temporal succession, that is, less than 500 msec apart. The dependent variable is reaction time, defined as the time between the onset of a stimulus and the onset of a response associated with it. The time between the two stimuli is called the *interstimulus interval* (ISI). The rationale behind the PRP paradigm is simple: Try to reduce complicated events to their basic format. Two stimuli are the absolute minimum for inducing attentional

overload. It is far easier to make inferences based upon a simple task with only two stimuli than upon a more complicated paradigm like time-sharing, where many aspects of the component tasks can be confounded (Kantowitz & Knight, 1976a). Yet even with this relatively simple paradigm there is a plethora of possible explanations, as we shall see.

The basic finding in the PRP paradigm is an increase in reaction time to the second signal (RT_2) when ISI decreases. This is easily explained by the limited-capacity model. Since the channel is busy processing the first stimulus, processing of any subsequent stimulus information must be delayed because the channel is basically a serial device. Of course, if the combined load of both first and second stimuli was low and within channel capacity, no RT delay would occur, but this outcome is largely restricted to sets of Donders A reactions (see Kantowitz, 1974 for a review). The shorter the ISI, the less time is available for the channel to process the first stimulus before occurrence of the second stimulus; thus, the second stimulus must wait longer to enter the channel at shorter ISIs. This waiting inflates RT_2 , which is measured from stimulus onset and not from the time the stimulus enters the channel.

It is easy to test the limited-capacity model because it makes strong predictions about the PRP paradigm. One such prediction concerns the effect of increasing the information load of the first S-R pair (by increasing the number of S-R alternatives from say, one to two to four, etc.). This should increase RT_2 by a constant amount at each increment, resulting in parallel RT_2 functions, one for each S_1 - R_1 load. (See Kantowitz, 1974, Table 2 for a numerical example of this.) But when this was tested (e.g., Karlin & Kestenbaum, 1968) the difference in RT_2 as a function of member of S-R alternatives

decreased as ISI decreased, instead of remaining constant.

Other strong predictions have also fared poorly. The limited-channel model predicts that reaction time to the first stimulus (RT_1) should remain unaffected by either ISI or difficulty of the second S-R pair because the first stimulus has already entered the channel by the time the second stimulus has occurred. But a review of RT_1 effects (Herman & Kantowitz, 1970) finds that RT_1 is influenced by ISI. Indeed, if error rates are constant, RT_1 declines over ISI in a manner roughly similar to RT_2 . Similarly, increasing the informational load of the second S-R pair causes increases in RT_1 (Kantowitz, 1974).

It is clear that in a PRP paradigm where the limited-channel model makes very precise predictions, the model fails. However, it should be noted that other models (to be discussed later) may appear to do better only because they are more ambiguous and do not make precise predictions. And models that do make equally precise predictions as the limited-channel model are difficult to apply to other types of overload paradigms.

Probe RT. The probe task is becoming more and more popular in the study of attention (Kerr, 1973). A reaction-time task, called the probe, is inserted at various times in relation to a primary task. This overloads the human, but only momentarily. The logic behind the probe task is simple. It is assumed that the primary task occupies some proportion of available channel capacity. Any excess capacity is thus available for probe processing. So reaction time to the probe signal is interpreted as an indicant of available processing capacity. Note that this logic assumes that capacity is not suddenly diverted to the probe task, at the expense of the primary task. An assortment of single-task-only control con-

ditions is necessary to check on the validity of this assumption. The advantage of the probe paradigm is that it can sweep out the temporal changes in capacity demands of the primary task, since the probe stimulus can be presented during any phase of the primary task.

Posner's and Keele's study (1969) is typical of this paradigm. These researchers were interested in the attention demands of a motor response: moving to a target. They found greater probe RT for a narrow target than for a wide target and concluded that the aiming requirements of smaller targets demanded more attention. Taking advantage of the probe paradigm to sweep out attentional demands, they found a U-shaped function with elevated probe RT at the start and end of a wrist rotation. A more detailed follow-up study, Eells (1973), agreed that narrow targets gave greater probe RT but found RT to decrease continuously as the target was approached. This apparent contradiction—all the more puzzling because the two studies were conducted at the same university—was resolved by Salmoni, Sullivan, and Starkes (1976), who realized that the probability of occurrence of the probe signal was two-thirds in the Posner-Keele study and 1.0 in the Eells study. They were able to replicate both findings by varying probe probability. (However, Salmoni et al. had some other problems with their procedure; see Kantowitz & Knight, 1978, for details.)

The point of this discussion is to emphasize the dangers of the probe paradigm. It offers great potential, but investigators must be extremely careful to avoid conclusions based upon limitations of the methodology.

Modality Effects in Serial and Free Recall. Is information better if it is presented visually or auditorily? If you were required to remember in order a

short list of digits presented to you, would it be better if you read them (visual presentation) or if someone else read them to you (auditory presentation) at the same rate? Would recall be better if you both saw them and heard them than if you only saw or heard them? These fundamental questions have led to much research on the effect of presentation modality on memory.

A representative study is Murdock and Walker (1969, Experiment 1). Individuals were given lists of 20 words that were to be recalled in any order (free recall). The words were presented at either a one-second or two-second rate (that is, one word presented every one or two seconds), and for some lists the words were presented visually over a slide projector while for other lists presentation was auditory via a tape recorder. After individuals studied and recalled five practice lists, they were tested on 20 more lists, with 5 lists given at each of the four combinations of modality and presentation rate. The effects of varying modality were generally the same at both presentation rates: For the first 15 of the 20 words there was not much difference in recall between having heard the lists and having seen them, but for the last 5 items recall was much better if the words had been presented auditorily than if they had been presented visually. This last finding is referred to as the *modality effect*: Immediate recall of the last few items in a series is better if the items are presented auditorily than if they are presented visually.

The same outcome is obtained when persons are given shorter lists and asked to recall the items in the order in which they were presented (a serial-recall task). Again, recall is better for the last couple of items presented auditorily, with there being little or no difference between

visual and auditory presentation for the initial and middle items in the list (e.g., Crowder, 1970). The modality effect is believed to occur because auditory information lingers in the nervous system a bit longer than visual information in a relatively raw, unprocessed form. Thus, when persons recall a list after it is presented auditorily they can rely on this little "echo" to recall better the last few items in the list (Crowder & Morton, 1969). The advantage of this echoic storage, as it is called, only affects the last few items of the list because the echo of the earlier items has either faded away or been displaced by later items by the end of the list.

Thus we cannot generally conclude that "listening is better than reading," because it is only under special conditions that this is so. It is only the last few items of an auditorily presented list that are better recalled, and only when the recall test is given soon after presentation. There appear to be few long-term effects of modality of presentation. For example, when Kintsch and Kozminsky (1977) had people summarize stories after either reading them or listening to them, they found little difference in performance.

Effects of Orienting Tasks on Recall. Under Proposition 5 we discussed the levels-of-processing approach to memory, by which retention is considered to be a function of the level of processing that a stimulus receives when it is initially processed. The example of listening to words in a language one does not know very well was used to illustrate how information could be processed to different depths. One laboratory task that has been used in an attempt to capture the processing of information to different depths is referred to as the use of different orienting tasks in incidental learning (Hyde &

Jenkins, 1969). This takes a bit of explaining. In most memory experiments individuals are explicitly told that they will later be tested on the information with which they are presented (intentional learning). This condition is relatively rare in real life outside the setting of schools. We rarely "study" our experience for an explicit memory test later. Unlike the intentional learning situations that are commonly explored in memory experiments, in incidental learning paradigms people are exposed to information without being told that they will be tested on it later. Instead the material is presented under the guise of performing other tasks with it, and then the later memory test for the material comes as a surprise. The tasks used to present material to the individuals are referred to as *orienting tasks* and different orienting tasks can be chosen that are supposed to determine the level or depth of processing of the material.

An example of an experiment illustrating this logic is Craik and Tulving (1975, Experiment 2). People were told that the experiment was concerned with their speed of reaction in answering simple questions. They were shown a list of 60 words about which they were supposed to answer yes/no questions by pressing one of two buttons. The word was presented for 200 msec ($1/5$ of a second), and the people were required to answer the question about each word as rapidly as possible by pressing the *yes* or *no* response keys.

There were three types of questions designed to provide for different levels of processing of the words. For some words the question was simply, "Is the word in capital letters?" This defined a structural level of processing where all the participants had to do to answer the question was examine the type in which

the word appeared. There was no need to process the word to deeper levels, such as ascertaining its meaning, in order to answer the question. Half the time the word would be printed in upper-case letters, the other half in lower-case letters, so that people responded yes and no equally often. For other words, participants were asked whether or not the word rhymed with a second word. They might be given the question, "Does it rhyme with weight?" and the word presented might be *crate* (a yes response) or *market* (a no response). These questions were meant to induce a phonological level of processing where participants had to at least process the sound of the words. Finally, the questions preceding other words were meant to induce people to determine their meaning. They were asked if the words would fit in a sentence such as "He met a _____ in the street." For yes responses the presented word might be *friend*, for no responses it might be *cloud*.

Each person was given 20 words in each of the three question conditions (structural, phonological, and sentence), and for 10 questions in each condition the answer was yes, while for the other 10 conditions the answer was no. One other important aspect of the procedure was that across all participants in the experiment all the words were used equally often in all six conditions (three questions with yes or no answers to each question). Thus the effects of condition were not due to there being different words in the conditions.

The effects of these different encoding manipulations were measured by a yes/no recognition test. Participants were given a sheet with 180 words on it, and their task was to go through it and circle the 60 words they had seen earlier in the experiment. The 60 target words were

randomly mixed in with the 120 "lures," or distractor words. (It should be remembered that this recognition test was unexpected.) For words that participants responded yes to, the proportion correctly recognized was 0.15 in the structural condition, 0.47 in the phonemic condition, and 0.83 in the sentence condition (numbers estimated from Craik & Tulving, 1975, Figure 1). The results were similar for the conditions in which people responded no, but the differences were not as large (0.19, 0.25, and 0.49 recognized in the structural, phonemic, and sentence conditions, respectively). These results indicate that the use of different orienting tasks has a dramatic effect on the recognition of words. If people are given *table*, having just been asked "Is the word in capital letters?" they will recognize it on a later test only 15% of the time. Yet if they were presented the same word but asked if it fit in an appropriate sentence, later recognition would be 81%. While many theories of memory have little to say about the very large difference in memorability under these conditions, according to the levels-of-processing framework the words differ so greatly in their memorability because of the different depths of processing they received when they were initially studied.

State-Dependent Retrieval in Cued and Free Recall. One common tale often told about alcoholics is that they will do something while intoxicated, such as hide some money, and then not be able to recall where they hid it when they have sobered up. This is referred to as *alcoholic amnesia*, as is the more common experience of not being able to recall very well what happens while drunk. However, when alcoholics again become intoxicated, they may recall where they hid their money. This appears then to be

a case of state-dependent retrieval. Experiences are better recalled when retrieval is attempted in the same state as when they were originally learned rather than in a different state. This process has been studied experimentally in both animals and humans.

An interesting representative study of state-dependent retrieval with marijuana has been reported in Eich, Weingartner, Stillman, and Gillin (1975). Participants were told that the study was concerned with the effects of marijuana on memory. They were given a cigarette to smoke prior to having their memories tested. For half the participants the cigarettes contained marijuana, while for the other half the cigarette tasted like marijuana but did not have its active ingredient (a placebo condition). After smoking, participants heard a list of 48 words, with instructions to try to remember them for a later test. The lists contained four words from each of 12 semantic categories (e.g., type of vehicle—*streetcar, bus, helicopter, train*). Participants recalled each list some four hours after it had been presented. Half the individuals who learned the words under marijuana were tested again under marijuana, while half were tested after smoking a placebo cigarette. Similarly, for placebo participants half were tested after smoking another placebo and half were tested under marijuana.

The results showed that people who studied words after smoking marijuana tended to recall fewer than those who studied them after smoking the placebo cigarette. Thus marijuana reduced recall. However, the more interesting effect is that people who both studied and recalled the list while under the influence of marijuana recalled more words than others who studied the list after smoking marijuana but who then were tested after

smoking the placebo cigarette. Thus, if the list were learned while under the influence of marijuana, it was recalled better when tested under marijuana than when not. This outcome is referred to as *state-dependent retrieval*.

Other participants were treated identically to those just described, except that at recall they were tested under conditions of cued recall rather than free recall. These cued-recall participants were given the category names and asked to recall as many items as possible from the categories. Under conditions of category-name cued recall, the state-dependent retrieval effect was not found. That is, participants who studied and were tested under the influence of marijuana recalled no more words than those who studied while under its influence but who then were tested while sober. This outcome shows that powerful retrieval cues can override the state-dependent retrieval effect (see Eich, 1977, for further discussion).

IMPLICATIONS

Theoretical

It should be clear that the information-processing research described above has called into question many details about the limited-capacity channel model. The model has been the "victim" of the great amount of research it has engendered; this is a happy outcome for any psychological theory. But the most important basic assumption of the model—that behavior can be explained in terms of internal information flow—has been very strongly supported. Any arguments concern the details of the postulated flow of information within the organism.

The major change in the model has been to allow selectivity to occur at

stages other than the filter (Broadbent, 1971). In particular, the major bottleneck in attention has been moved away from the stimulus or input end of the chain of processing stages towards the response or output end (Kantowitz, 1974). Some models have been offered that completely relax input restrictions by stating that early in the processing chain information can be handled in parallel (Keele, 1973). This class of model has no bottleneck in early processing stages.

Another important advance has been the realization that the postulated capacity demands of a processing stage are not independent of the configuration of the set of stages (Townsend, 1974). While it was once believed that the serial nature of the original limited-capacity model was a natural consequence of processing a finite rate of information through the channel, we now know that parallel models with limited capacity are quite feasible. Indeed, we can in certain situations create parallel models that make exactly the same predictions as other serial models. So two major items are required in any model that attempts to chart information flow through the organism. First, the arrangement of stages must be specified. This can be serial, parallel or a mixture of both (hybrid). Then the capacity demands of different stages must be defined. It will not always prove possible to distinguish particular models within a given class, and this is why information-processing research tries to limit and to compare *classes* of models. By manipulating information flow and capacity requirements, very powerful and flexible information-processing models can be obtained. This is quite appropriate, since the capabilities of the human information processor cannot easily be captured by simple theories based only upon reflexes and S-R associations.

Several important theoretical implica-

tions can also be drawn from the memory research that has been reviewed in this chapter. For many years students of memory and verbal learning have examined the effects of overt stimulus characteristics on memory. Thus, for example, numerous studies have been carried out in which such variables as word length, frequency of occurrence in English, rated meaningfulness of words, and the degree to which the word is associated with others were examined. All these stimulus characteristics and several others can be shown to affect later recall of stimuli to a greater or lesser (usually lesser) extent. One of the conclusions to be drawn from experiments such as that of Craik and Tulving (1975) is that even when all these overt stimulus characteristics are held constant by giving individuals the same words, memory can be varied quite dramatically by having persons perform different mental operations when they are presented with the stimuli. This points up the need to consider internal mental events as crucial parts of any memory theory and not just overt stimulus characteristics of the material to be learned.

Another broad theoretical message that can be presented on the basis of the research is that it is not enough simply to describe memory in terms of characteristics of memory traces. Memory traces may be strong, deep, or what have you, but recall will not occur unless there are appropriate cues in the retrieval environment to allow access to the traces of past experience. Memory is always a product of information from two sources, the memory trace and the cues in the retrieval environment.

To summarize, the research reviewed in this chapter supports three broad theoretical conclusions: First, the single-channel model of information processing has been found faulty in some respects, but the characterization of mental events

in terms of information flow has proved extremely useful. Second, the nature of the mental operations used in processing information greatly affects how well it will later be remembered. Third, not just the nature of the information encoded but also the nature of the retrieval cues determine how well some fact or experience will be remembered.

Practical

A number of practical implications may be drawn from current research on information processing and memory. Understanding the nature of information processing and memory through basic research is often useful in attempts to facilitate these matters in human affairs. In today's world there is an information glut. We are being exposed to a tremendous amount of information and are expected to know more and more about complicated aspects of our world. How can we most efficiently arrange this information so that it can be best processed? What steps can be taken to remember the great quantities of information that we are expected to know? How can we design machines so that they will better mesh with the information-processing capacities of humans? This last area of applied information-processing psychology is called human factors (McCormick, 1976). In this section we illustrate some ways to improve memory and also some instances of improved human factors design derived from models of information processing.

Improving Memory. Research reviewed in this chapter has revealed two major factors that influence recall: mental operations performed when a stimulus is being learned, and the nature of retrieval cues provided at the time of test. If both these factors could be included in some way in one memory technique,

this technique should greatly aid memory. In fact, this is exactly the case in the most successful mnemonic devices or memory techniques. They encourage people to perform a useful mental operation when studying the material, and they also supply a person with a powerful set of retrieval cues for later recall. The mnemonic devices reviewed here were developed long ago on a trial-and-error basis, but they can be profitably considered in light of modern memory research. Three of the most common mnemonic devices are: the link method, the method of loci, and the peg method.

The *link method* is quite simple. Suppose you have a 20-item shopping list to remember. What you would do is take the first two items on the shopping list, say bread and milk, and form vivid visual images of them. Then you would link the images of these two objects together in some way, preferably so that the objects are interacting. For example, you might imagine a giant carton of milk standing on a large loaf of bread. (It is often advised that images will be better remembered if they are bizarre rather than mundane, but recent evidence indicates that what is important is that the images be interacting, not bizarre; see Wollen, Weber, & Lowry, 1972.) Then you would take the third object and link an image of it to the second. If the third object is eggs, you might imagine the milk carton rolling off the loaf of bread and smashing down on the eggs. You would proceed through the entire list using the same principle; each successive object should be linked to its predecessor through an interacting image. This method is known as the link method because the items are linked together in this way.

When you get to the store and want to recall the objects, you would recall the first one and then examine the mental

image to see what it is linked to. (If you think you would not be able to remember even the first object, you might link it to your wristwatch or some other object that will be at the store.) Thus when you recall bread, it will be quite easy to recall that milk was next on the list, since in your image the large milk carton is sitting on the bread. When the milk topples off onto the eggs, it will serve as a cue for the next item on the list, and so on. The formation of visual images serves as a very potent mental operation for securing appropriate memory traces, while the linking of these items together through interactive images allows each to serve as a retrieval cue for the next.

The link mnemonic is a simple and effective technique that requires little practice. However, there are two drawbacks that make it somewhat less efficient than the two other techniques to be discussed. If one item in the list is forgotten, then the chain is broken and that item cannot serve as a cue for the next item. The rememberer must then be able to break back into the chain of images at some other point. Thus the link method depends on recall of past items to guarantee good cues for recall of additional items. Another difficulty with the link method is that people are required to recall the items in order. If you wanted to know the 15th item on the list, you would have to go through the first 14 to get to it. The case would be similar if you wanted to recall items 10 through 20; you would first have to recall items 1 through 10.

The other two mnemonic devices, the method of loci and the peg method, do not suffer from both these drawbacks, but they do involve a greater initial investment in terms of learning the method. Both these methods, like the link method, are founded on the use of mental imagery

and effective retrieval cues. The *method of loci* has already been briefly discussed in the Propositions section. In order to use this device you must first choose a path that is known very well and that has a number of discrete locations. For example, you might select the path used in walking to school and attending classes every day, or a path in your neighborhood, or a set of locations in a house or some other familiar building. The important points are that the path chosen be one that will not be forgotten, and that it has a number of discrete, easily identifiable, locations.

The trick to the method of loci is that when learning some material, such as the 20-item shopping list, each item should be converted into an image and deposited in the discrete location as you mentally walk down the path. Thus if you wanted to remember bread, milk, and eggs as the first three items, you would mentally imagine yourself walking down the path and, in the first three locations that you came to, depositing an image of the appropriate object. You would continue in this fashion until you had deposited all the objects. Then when you got to the store and wanted to recall the objects, you would again mentally imagine yourself walking down the path and looking in each location for the appropriate object. This technique may sound far-fetched, but it is really quite effective. If you practiced it you would see how easy and efficient it really is (Bower, 1970). Notice that in this case if you forget one item in the list (you cannot "see it" at the proper location) this would not prevent you from recalling the next item, as in the link method. However, it would still be difficult to call out the 15th item without mentally walking along the path to recall the first 14. The method of loci is quite effective since the locations on

the path that serve as the retrieval cues are not in danger of being forgotten, thus supplying more or less permanent cues, while the traces of items in the locations are made retrievable by the operation of mental imagery.

The *peg method* is quite similar to the method of loci and operates on the same principles. One must invest an initial amount of time in learning a series of pegs that will later serve as retrieval cues in the same way that locations do in the method of loci. There are a great number of peg systems, with a range of up to 1,000 pegs that can serve as retrieval cues. One of the simplest peg systems is based on rhymes for the numbers 1 to 20. The first few are "one is a gun," "two is a shoe," "three is a tree," "four is a door" and so on. You can make up your own, or see Bower and Reitman (1972) for a list of 20. After this list has been learned perfectly, then you can use it for remembering additional information. Again consider the hypothetical grocery list. If the first item is bread, you would form an interacting image between a loaf of bread and the referent of the word that rhymes with one, that is gun. Thus you might imagine a gun shooting a loaf of bread. Similarly, for milk you might image a shoe stuffed into a milk carton. This would continue until every item in the shopping list had been associated to an image of the object that rhymed with a number. When it is necessary to recall the list, there is a set of retrieval cues in the form of the numbers 1 to 20 that are in no danger of being forgotten, and the rhymes to those numbers which have been learned to perfection. Thus to recall the first item, you need to recall that "one is a gun" and then "look at" the image of gun to see what the gun is shooting. The process is the same for recalling the other items in the list.

Once again, the effectiveness of the mnemonic device depends on the use of interactive imagery and the provision of excellent and relatively permanent retrieval cues. The peg method does not depend for its success on recall of previous items, as does the link method, and also with the peg method it is possible to recall a particular item out of order. If the 15th item were desired, one could find the rhyme for 15, then look up the appropriate image.

Mnemonic devices are quite effective for remembering large amounts of information, especially if the information is concrete and one can easily form images of the material (see Paivio, 1971, Chap. 6 for further discussion). These devices can also be made to work for abstract material, but with this sort of material it will take longer to create the appropriate images (Paivio, 1969). Other types of mnemonic systems, many of which are simply variations on the methods already discussed, have been devised to aid recall of faces and names, dates, playing cards and other useful stimuli. One of the better practical books on these methods is Lorayne and Lucas (1974).

Human Factors. We have briefly referred to one important human factors area that has greatly benefited from information-processing research: air traffic control. Broadbent's original discovery that traffic controllers could perform much better when the voice of each pilot came from a separate loudspeaker was only the start of a great deal of applied research. The basic principle of human factors is that it is far more efficient and economic to redesign machines to interface smoothly with people than to train people to deal with poorly designed machines. In order to optimize the person-machine interface we must know enough about human information processing to

tell the equipment designer what forms of information input and control or response output are most convenient for the operator. Then systems can be designed to meet these criteria. Even though the machine may be slightly more complicated as a result of human factors analysis, the entire person-machine system will operate better and more reliably.

A simple example shows how the memory capability of the aircraft controller was artificially improved by human factors. In early air traffic control systems the operator had a radar screen on which each airplane was represented only by a dot. In order to match dots to aircraft in the sky, the controller would order sharp maneuvers—such as a 90° turn—that would show up clearly on the radar-scope. Sometimes this sharp maneuver would place two aircraft in potential conflict. In modern systems every commercial aircraft has a beacon that sends out a coded signal. The radar screen identifies planes by the label sent from the beacon. This greatly reduces the memory load imposed on the controller, allowing the safe control of more aircraft.

Another problem area in air traffic control concerns the approach to the landing runway. While it is the pilot's responsibility to keep the plane at the proper altitude during descent, it is nevertheless standard procedure for the controller to warn the pilot if it descends below the glide path. In order to do this, the radar screens also display the planes' altitude. However, research on attention has indicated that the more things we make the controller keep track of, the more likely is channel capacity to be exceeded. In the past, accidents have occurred because pilots have literally flown planes into the ground—this is called a "controlled descent into terrain" in pilot jargon, to distinguish it from a crash

where the pilot could not control the plane—without being warned by controllers. The usual response to criticism of the controller is a reply that altitude is the pilot's responsibility. A more helpful approach has been to augment the radar display so that whenever a plane descends below a critical altitude it automatically starts to flash on the radar screen. This immediately gets the controller's attention so that the pilot can be quickly warned.

Human factors research extends into more prosaic areas of life, such as the design of a bathroom fixture. We know from information-processing research that people find it difficult to combine different sources of information. Yet when you take a shower you often must do this. To obtain a desired temperature you must adjust the volume of hot and cold water sources separately. Newer shower controls have a single dial that rotates to control temperature and shifts up and down to control volume. Instead of having to integrate two separate sources of water (and information), this control permits simple decisions about temperature and volume to be made independently.

SUMMARY

Inferring the flow of information and the transformations effected during this flow within the organism is difficult. Yet the richness of behavior and in particular the adaptability of the human information processor demand no less than this kind of effort. The search for mental events in psychology goes back a long way. Its rejection by early behaviorists was appropriate because the tools for such a mentalistic adventure were poorly formed and improperly used. Now our technology and theory have matured to

the point where the pursuit of mental events is a proper scientific topic.

We have seen that the life of an information-processing model is relatively short. Such sturdy models as the limited-capacity channel are already under major attack. This is a tribute to the vigor and amount of research such models have engendered. Once the more obvious aspects of behavior have been tested and confirmed, it is only natural to proceed to finer and finer details that eventually modify or even reject the model that started all the research. Thus, the logic and basic conceptual framework of the information-processing approach is more important than any one single model. Efforts to characterize the information flow inside the organism have greatly expanded our ability to understand and to predict human behavior in complex situations that are not easily analyzed within either traditional or neo-behavioristic learning theories. The refinements of chronometric analysis, levels of processing, and other endeavors have just begun.

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Anderson, J. R., & Bower, G. H. *Human associative memory*. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1973.

In this thorough presentation of the associative theory of memory, the history of associationism is traced and a new computer simulation model (HAM, for Human Associative Memory) is developed. It is applied to a number of experimental situations, from memory for word lists to more complex processes such as sentence memory and question answering.

Broadbent, D. E. *Decision and stress*. New York: Academic Press, 1971.

This is an advanced graduate treatise which traces the development of Broadbent's 1958 limited-capacity model. Each

chapter starts with a concise statement of the position in 1958 and then reviews recent research efforts. The implications of this research for the model are discussed in detail, and the model is thereby substantially revised and updated.

While the book is valuable for the theoretical framework erected to house these new data, it is even more useful as an exercise in scientific logic. It shows how information-processing approaches utilize data to modify models and mechanisms. The interaction between data and model is made clear. The reader comes to appreciate that any static picture of the current state of information-processing research is incomplete; what is important is the method of attacking problems.

Crowder, R. G. *Principles of learning and memory*. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1976.

This is one of the more comprehensive textbooks in the field, appropriate for advanced undergraduates or graduate students. A variety of topics is considered in some depth, including sensory memory systems, short-term memory systems, and different aspects of long-term memory and forgetting. One chapter is devoted to non-verbal memory, but most are concerned with verbal memory. A number of distinct theoretical approaches are considered; separate chapters consider the interference theory of forgetting, organization of memory as reflected in free recall, serial organization in memory, and retrieval processes.

Kantowitz, B. H. (Ed.). *Human information processing: Tutorials in performance and cognition*. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1974.

This text is designed to serve beginning graduate students. Each chapter is carefully developed, with minimal assumptions about the reader's background. There is heavy emphasis on methodology. The topics are arranged in a continuum starting with human performance and progressively becoming more cognitive; the final chapter is on computer simulation of thought. Intervening chapters discuss the interpretation of reaction-time data within an information-processing framework, double stimulation

and attention, mathematical models of capacity and serial versus parallel processing, cognitive representations of serial patterns, and the perception of printed English.

Kintsch, W. *The representation of meaning in memory*. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1974.

This is an advanced treatment of a number of topics concerned with the processing and remembering of information from prose texts. Basically it contains a statement of Kintsch's influential work and the experimental work that has been done to test and to evaluate his theory. Parts of the book were written in conjunction with students who aided in the research. Although by design it presents a rather partisan approach, it does survey a generous number of interesting problems and presents a good deal of experimental work.

Melton, A. W., & Martin, E. D. *Coding processes in human memory*. Washington, D.C.: V. H. Winston, 1972.

This collection of chapters considers many different aspects of human memory. The contributors are all well known for their work in cognitive psychology, and several of the chapters serve as surveys of their work. Authors of other chapters have chosen to present a statement of some theoretical position or viewpoint. One theme of the book, as the title implies, is how information that is to be remembered is coded in memory. The chapters are uniformly well written, and this book allows the interested student to examine a variety of topics concerned with memory as approached by some of the most influential theorists in the field.

Posner, M. I. *Chronometric explorations of mind*. Hillsdale, N.J.: Lawrence Erlbaum Associates, 1978.

This book describes the author's research program over many years in which the mind is studied by analyzing the time course of internal information flow. Attempts are made to relate human performance and physiological techniques. The book starts with an interesting review of the history of mental chronometry. Later topics are processing systems, coordination

of codes, psychological pathways, alertness, conscious attention, and orienting. It concludes with a discussion of implications of this style of research for practical areas like reading, development of intelligence, and personality.

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