Attention and Effort

DANIEL KAHNEMAN
The Hebrew University of Jerusalem

PRENTICE-HALL, INC., *Englewood Cliffs, New Jersey*

Library of Congress Cataloging in Publication Data

Kahneman, Daniel
Attention and effort.

(Prentice-Hall series in experimental psychology)
1. Attention. I. Title.
BF321.K26 155.7'33 73-3375
ISBN 0-13-050518-8

To

Irah, Michael and Lenore

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Prentice-Hall International, Inc., *London*
Prentice-Hall of Australia, Pty. Ltd., *Sydney*
Prentice-Hall of Canada, Ltd., *Toronto*
Prentice-Hall of India Private Limited, *New Delhi*
Prentice-Hall of Japan, Inc., *Tokyo*

Contents

Preface

There are several distinct subcultures among students of attention: investigators whose background is in studies of audition, others who think in terms of visual perception, others who are primarily interested in speeded performance, and some who study physiological arousal and its multiple psychological determinants. Each of these subcultures has tended to evolve its own language, and its particular conventions concerning the choice of experimental manipulations and of dependent variables. Each has also developed its own biases. I have attempted in this book to incorporate findings and ideas from these disparate sources into a coherent formulation of attention.

The book is intended for graduate students and for advanced undergraduates studying the role of attention in perception and in performance. It consists primarily of a review of the research areas that are commonly grouped under the label 'attention.' While the book presents a particular interpretation of this research, I hope it may be useful to students and to teachers who do not share this interpretation.

As will be evident to the reader, I have learned much of what I know about attention from Donald Broadbent and Anne Treisman. It will also be obvious that I find Ulric Neisser's approach to perception and to cognition very congenial. A less obvious but equally important intellectual debt is to the late David Rapaport. While serving as his research assistant for one summer many years ago, I was introduced to the psychoanalytic view of attention as energy. Many years later, having become (as I thought) a rather tough-minded experimental psychologist, I was surprised to discover that my understanding of attention bears the permanent imprint of that encounter.

This text owes its existence to Jacques Mehler, who suggested several years ago that I write a chapter on attention, and who patiently prodded me through these years, while a misshapen chapter finally evolved into a book. The conception of the book was influenced by my students and collaborators, Daniel Gopher and Anat Ninio, who insistently demanded a clarification of my own views, and who also contributed to that clarification. Frequent discussions and friendly disagreements with Michael Posner and Steven Keele during the year that I spent in Oregon inspired much of the material in the present version. I have benefited from their scholarship as well as from their intellectual generosity. The text also bears the marks of comments by my wife Irah, by Ulric Neisser, Paul Obrist, Anne Treisman, Barbara and Amos Tversky.

Some of the ideas in this book were shaped by the results of experiments carried out in my laboratory at the Hebrew University. I learned much from the students who conducted several of these studies: Uri Avner, Avishai Henik, Ditza Kafry, Nurit Lass, Rina Levy and Eythan Weg. Several able assistants participated in the project: Absalom Bauman, David Bigeliter, Itamar Gatti, Ruth Kimchi, Noa Klein and David Shinar. Yitzchak Hadani provided the technical expertise that made the experiments possible.

In the preparation of the book I had valuable bibliographical help from Bernard Goitein and Ilan Shapiro, and help that went well beyond the standard secretarial duties from Tamar Ziv, Nira Rebaisen and Leila Berner at the Hebrew University, from Meredith Woodward and Karon Johnson at the Oregon Research Institute.

The book was completed during a sabbatical year spent at the Oregon Research Institute and it is indeed a pleasure to acknowledge the marvelous hospitality and the intellectual stimulation of my colleagues in that institution.

Finally, it is a pleasant duty to admit that this work could not have been completed without financial support from various sources: The Center for the Study of Disadvantaged Children and the Central Research Authority at the Hebrew University of Jerusalem, and Grant No. 5 S01 RR 05612 to the Oregon Research Institute.

D.K.

Jerusalem, 1973

1

Basic Issues in the Study of Attention

The concept of attention has had an uneven career in the history of academic psychology. When that history began in the nineteenth century, the study of the effects of attention was a favorite topic for introspection, and Titchener (1908) could confidently assert that ". . . the doctrine of attention is the nerve of the whole psychological system, and that as men judge of it, so shall they be judged before the general tribunal of psychology [p. 173]." This was perhaps a valid judgment of the importance of attention, but certainly a poor prediction of the development of scientific psychology. Within a few years of Titchener's pronouncement, the most vital movements in psychology were the Gestalt and Behaviorist schools, and both movements attempted to do without the concept of attention—for essentially the same reason. Although differing in their method of investigation and in the very aims of their research, the Behaviorists and Gestalt theorists shared the conviction that the operations which relate output (response, or percept) to input (stimulus, or field) conform to a simple and straightforward set of rules, such as isomorphism or conditioning. The concept of attention was unpopular because it is most applicable where simple rules break down. Only the functionalists, who were more interested in describing behavior than in developing theories about it, kept alive the concern with specific aspects of attention such as the preparatory set and the span of apprehension. The term "attention" was effectively banished from the vocabulary of scientific psychology: the dominant theorists of the day found it useless, and the empirically inclined functionalists were more concerned with the trees than with the forest. Thus, in 1953 Osgood published an important text which covered the entire field of experimental psychology and mentioned "attention" only once, in the discussion of a particular theory of discrimination learning.

By the end of the 1950s, the situation had altered radically, and the newly legitimized concept of attention was a central topic in an emergent cognitive psychology. The new Zeitgeist ascribed more spontaneity and autonomy to the organism than had the classical doctrines of behaviorism, Gestalt theory, and psychoanalysis. Spontaneity and autonomy imply some degree of local unpredictability. Indeed, the main function of the term "attention" in post-behavioristic psychology is to provide a label for some of the internal mechanisms that determine the significance of stimuli and thereby make it impossible to predict behavior by stimulus considerations alone.

SELECTIVE ASPECTS OF ATTENTION

The existence of mechanisms that control the significance of stimuli can hardly be denied. For example, a pigeon may learn to favor a red triangle over a green circle. On a subsequent transfer test, will the pigeon favor a red circle over a green triangle, or will he prefer the triangle? The behavior of different pigeons leads to different answers; the psychologist is tempted to state—not very helpfully—that some pigeons attend to shape while others attend to color. A sailor of the British Royal Navy enduring a period of servitude in a psychological laboratory is presented with two simultaneous instructions on different loudspeakers; he obeys one and is apparently oblivious to the other. A Harvard sophomore is trained to locate specific letters in a large array, and he eventually reports that whatever letter is designated as target seems to erupt spontaneously from an indistinct background. In a Russian laboratory, a dog is strapped and harnessed in front of a speaker and a tone is sounded at regular intervals. When a tone of different pitch is inserted in the series, the dog catches its breath, moves its eyes, and pricks its ears. Recordings of autonomic activity reveal that a complex yet orderly sequence of vascular and electrodermal changes follows the presentation of the novel tone.

In all these situations and in many others, the organism appears to control the choice of stimuli that will be allowed, in turn, to control its behavior. The organism *selectively attends* to some stimuli, or aspects of stimulation, in preference to others.

There are many variants of selective attention. The present work borrows a taxonomy of selective operations suggested by Treisman (1969). Attention tasks are classified according to what they require the subject to select: inputs (or stimuli) from a particular source; targets of a particular type; a particular attribute of objects; outputs (or responses) in a particular category. There is growing agreement that these varieties of selective attention are governed by different rules and are to be explained by different mechanisms.

INTENSIVE ASPECTS OF ATTENTION

There is more to attention than mere selection. In everyday language, the term "attention" also refers to an aspect of amount and intensity. The dictionary tells us that to attend is to apply oneself—presumably to some task or activity. Selection is implied, because there are always alternative activities in which one could engage, but any schoolboy knows that applying oneself is a matter of degree. Lulled into a pleasant state of drowsiness by his teacher's voice, the schoolboy does not merely fail to pay attention to what the teacher says; he has less attention to pay. A schoolboy who reads a detective story while his teacher speaks is guilty of improper selection. On the other hand, the drowsy schoolboy merely suffers from, or perhaps enjoys, a generally low level of attention.

A comprehensive treatment of the intensive aspect of attention was offered by Berlyne (1960). He suggested that the intensity of attention is related to the level of arousal, that arousal can be measured with the aid of electrophysiological techniques, and that it is largely controlled by the properties of the stimuli to which the organism is exposed. Berlyne (1951, 1960, 1970) also pioneered in the study of *collative* properties, such as novelty, complexity, and incongruity, which cause some stimuli to be more arousing than others. He observed that the more arousing stimuli generally tend to capture the control of behavior in situations of response conflict.

Berlyne was mainly concerned with involuntary attention. The collative properties that he studied control an involuntary selective process and they elicit an involuntary surge of arousal. A cognitive psychology, however, is not congenial to studies of involuntary behavior. Perhaps as a result, the line of investigation which Berlyne opened has not been followed very actively. In contrast, the study of voluntary selective attention has become one of the central topics of experimental psychology. In voluntary attention the subject attends to stimuli because they are relevant to a task that he has chosen to perform, not because of their arousing quality. The modern study of voluntary selective attention has therefore been conducted with little or no reference to arousal or to the intensive aspect of attention.

The present work contends that intensive aspects of attention must be considered in dealing with voluntary as well as with involuntary selection. For this integration to be possible, however, the intensive aspect of attention must be distinguished from the more inclusive concept of arousal. Thus, the schoolboy who pays attention is not merely wide awake, activated by his teacher's voice. He is performing work, expending his limited resources, and the more attention he pays, the harder he works. The example suggests that the intensive aspect of attention corresponds to effort rather than to mere wakefulness. In its physiological manifestations effort is a special case of arousal, but there is a difference between effort and other varieties of arousal, such as those produced by drugs or by loud noises: the effort that a subject invests at any one time corresponds to what he is doing, rather than to what is happening to him.

The identification of attention with effort suggests a reinterpretation of the correlation between arousal and involuntary attention. Novel and surprising stimuli which spontaneously attract attention also require a greater effort of processing than do more familiar stimuli. The surge of arousal that follows a novel stimulus represents, at least in part, a surge of mental effort. In this view, voluntary attention is an exertion of effort in activities which are selected by current plans and intentions. Involuntary attention is an exertion of effort in activities which are selected by more enduring dispositions.

As will be shown in Chapter 2, mental effort is reflected in manifestations of arousal, such as the dilation of the pupil of the eye or the electrodermal response. Furthermore, these measures follow second by second the fluctuations of effort. Finally, the transient variations in the effort that a subject invests in a task determine his ability to do something else at the same time. For example, imagine that you are conducting a conversation while driving an automobile through city traffic. As you prepare to turn into the traffic, you normally interrupt the conversation. Physiological measures would certainly indicate a surge of arousal at the same time, corresponding to the increased demands of the driving task.

A valid physiological measure of effort could contribute to the solution of a basic problem of experimental psychology: the measurement of various types of mental work in common units. The problem is indeed formidable: what common units can be applied to such activities as conversing, driving a car, memorizing lists, and observing pictures?

There has been one major attempt to solve this problem by using the terms and measures of a branch of applied mathematics called the theory of information (Attneave, 1959; Garner, 1962). This theory provides a measure of the complexity and unpredictability of both stimuli and responses, the "bit" of information. In the context of the theory, man is viewed as a communication channel that transmits information. The capacity of such a channel is given in bits/second, reflecting the rate at which information is transmitted through it. Channel capacity has been measured in human activities such as reading, driving a car, or playing the piano, as well as in the operation of systems such as telephone links or television sets. Unfortunately, estimates of human channel capacity in different tasks, or at different stages of practice, have been too inconsistent to be useful. Indeed, the variables of stimulus discriminability and stimulus-response compatibility are more powerful determinants of the speed and quality of performance than are the variables suggested by the information analysis (Fitts & Posner, 1967). As cognitive psychology abandoned the measures of information theory, it was left without a meaningful common unit to compare different tasks, and without a valid approach to the measurement of human capacity. Physiological measures of effort could contribute to fill these gaps.

BOTTLENECK MODELS OF ATTENTION

One of the classic dilemmas of psychology concerns the division of attention among concurrent streams of mental activity. Whether attention is unitary or divisible was hotly debated by introspectionists in the nineteenth century, by experimentalists since 1950, and the question is still unanswered. Much of the research that will be reviewed in this book was concerned directly or indirectly with this issue.

Two common observations are pertinent to the question of the unity of attention, but the answers they suggest are contradictory. The first of these observations is that man often performs several activities in parallel, such as driving and talking, and apparently divides his attention between the two activities. The second basic observation is obtained when two stimuli are presented at once: often, only one of them is perceived, while the other is completely ignored; if both are perceived, the responses that they elicit are often made in succession rather than simultaneously. The frequent occurrence of suppression or queuing in the organization of behavior suggests the image of a bottleneck, a stage of internal processing which can only operate on one stimulus or one response at a time.

Man's sensory and motor performance is obviously constrained by some bottlenecks in his biological constitution. Thus, man is equipped with only a narrow beam of clear and sharp vision, and he is therefore dependent on sequential scanning for a comprehensive look around him. He is also equipped with a single tongue and must therefore arrange his verbal responses in sequence. Attention theorists are concerned with the possibility that there are similarly limited stages in the central nervous system, which would make man unable to think, remember, perceive, or decide more than one thing at a time.

As Chapters 7 and 8 will show, the modern study of attention has been dominated by theories which assume a bottleneck stage somewhere in the system, but the locus of the bottleneck has been controversial. To introduce this issue, Figure 1-1 presents a crude outline of two models of selective attention, in which the bottleneck is located at different stages.

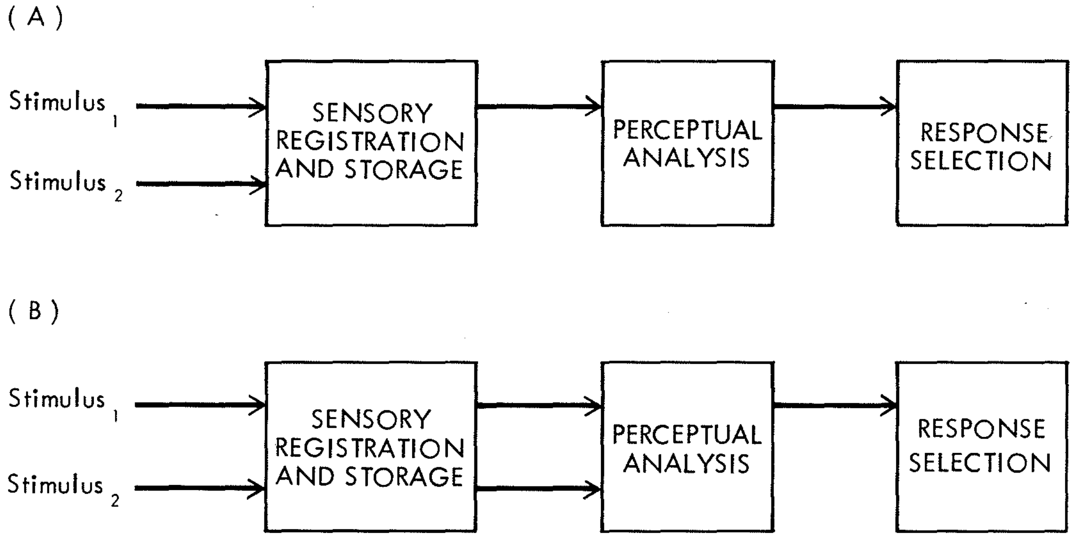

FIGURE 1-1
Two models of selective attention.

Model A illustrates some central aspects of the *filter theory* first proposed by Broadbent (1957a, 1958). This theory assumes a bottleneck at or just prior to the stage of perceptual analysis, so that only one stimulus at a time can be perceived. When two stimuli are presented at once, one of them is perceived immediately, while the sensory information that corresponds to the other is held briefly as an unanalyzed echo or image. The observer can attend to such echoes and images and perceive their content, but only after the perceptual analysis of the first message has been completed. In this model, attention controls perception.

In model B, which is associated with the names of Deutsch and Deutsch (1963), the bottleneck is located at or just prior to the stage of response selection. According to this model, the meanings of all concurrent stimuli are extracted in parallel and without interference. The bottleneck that imposes sequential processing is only encountered later: it prevents the initiation of more than one response at a time, and selects the response that best fits the requirements of the situation.

As an example of the questions to which the two models provide different answers, consider a person at a cocktail party who actively participates in one of the many loud conversations that take place in the room. Assuming that the sensory messages that correspond to several of these conversations reach the central nervous system of the listener, we may ask: at what point is the attended conversation favored over the others? To what stages of perceptual analysis do the unattended messages penetrate? According to filter theory (model A) the unattended messages are never decoded in perceptual analysis. In effect they are not "heard." According to model B, all the conversations are heard, but only one is responded to. The interested student who ponders Figure 1-1 will probably be able to invent several of the experiments which have been designed to answer such questions, and which will be discussed in some detail in Chapters 7 and 8.

The evidence of these studies indicates that selective attention to inputs affects perceptual analysis. This is contrary to model B. However, man is also capable of dividing his attention between concurrent messages. This is contrary to model A. Thus, one of the main conclusions of research on attention is that man's cognitive operations are far more flexible than either of these bottleneck theories would suggest.

While the allocation of attention is flexible and highly responsive to the intentions of the moment, there are pre-attentive mechanisms that operate autonomously, outside voluntary control (Neisser, 1967). These provide a preliminary organization to perception by a process of grouping and segmentation. The objects of perception are defined at that stage, and subsequent processes of selective attention operate on these objects. The general rule is that it is easy to focus attention exclusively on a single object and difficult to divide attention among several objects. Conversely, it is easy to notice several aspects or attributes of an object, but it is difficult or impossible to prevent the perceptual analysis of irrelevant attributes. Thus, we seem unable to see the shape of an object without seeing its color as well.

A CAPACITY MODEL OF ATTENTION

A capacity theory of attention provides an alternative to theories which explain man's limitations by assuming the existence of structural bottlenecks. Instead of such bottlenecks, a capacity theory assumes that there is a general limit on man's capacity to perform mental work. It also assumes that this limited capacity can be allocated with considerable freedom among concurrent activities (Moray, 1967). A capacity theory is a theory of how one pays attention to objects and to acts. In the present work, the terms "exert effort" and "invest capacity" will often be used as synonymous for "pay attention."

Prior to the introduction of a capacity model, it may be useful to briefly consider the question of how a mental activity is to be represented in a cognitive theory. As an example, consider such activities as "recognizing the visual word CAT," "rehearsing the word BLUE," or "deciding to press the right-hand key in the display." Theories of cognitive function usually assume that to each such activity there corresponds a hypothetical structure, and that the activity occurs when the state of the structure is temporarily altered. For example, many theorists would agree that there is a structure corresponding to the word CAT: it has been called a trace, a category state (Broadbent, 1971), a dictionary unit (Treisman, 1960), or a logogen (Keele, 1973; Morton, 1969a). Something happens in that structure whenever the word CAT is presented and recognized. The structure is specific, and its activation depends on the presence of the appropriate specific input.

It is already known that much of the basic sensory analysis of stimuli proceeds in this manner. Thus, there may be one or several neurons in the visual cortex which shift into a characteristic state of activity whenever any conceivable visual stimulus is presented, e.g., a corner-shape moving from left to right in a particular region of the retina.

The recognition of specific stimuli by specialized detectors provides an attractive model for a more general theory of the activation of cognitive structures. Indeed, it is tempting to think of the hypothetical structure which "recognizes" the input CAT as basically similar to a corner-detector. In such a system, the appropriate input (from the outside world or from the activity of other neural structures) serves as a key which releases some of the energy contained in the structure and causes it to generate outputs to serve as keys for other structures, and so forth. Because the structures do not share a common source of energy, considerations of overall capacity are not necessary to describe the system. Only the structural connections between components and the thresholds for the activation of each need to be specified. Structural models of the type illustrated in Figure 1-1 are most easily justified in such a view of information-processing.

Two observations of the present chapter suggest that such a description of information-transfer in man may be inadequate. First, it was noted that momentary variations in the difficulty of what a subject is trying to do are faithfully reflected in variations of his arousal level. There would seem to be little reason for such arousal variations if energy transfer plays no significant role in the system. The second observation was that the ability to perform several mental activities concurrently depends, at least in part, on the effort which each of these activities demands when performed in isolation. The driver who interrupts a conversation to make a turn is an example.

These observations suggest that the completion of a mental activity requires two types of input to the corresponding structure: an information input specific to that structure, and a nonspecific input, which may be variously labeled "effort," "capacity," or "attention." To explain man's limited ability to carry out multiple activities at the same time, a capacity theory assumes that the total amount of attention which can be deployed at any time is limited.

Not all activities of information-processing require an input of attention. The early stages of sensory analysis do not, since such elements as corner detectors can be activated by sensory inputs alone. Subsequent stages of perceptual analysis appear to demand some effort, because they are subject to interference by intense involvement in other mental activities. However, as Posner and Keele (1970) have noted, the demands for effort increase as one approaches the response-end of the system. It will be shown in Chapter 2 that covert activities such as rehearsal or mental arithmetic are highly demanding, as are all activities which are carried out under pressure of time.

A model of the allocation of capacity to mental activity is shown in Figure 1-2. The model should be read beginning with the boxes labeled Possible Activities. These boxes correspond to structures that have received an information input (not shown in the model). Each such structure can now be "activated," i.e., each of the possible activities can be made to occur, by an additional input of attention or effort from the limited capacity. Unless this additional input is supplied, the activity cannot be carried out. Any type of activity that demands attention would be represented in the model, since all such activities compete for the limited capacity. Activities that can be triggered by an information input alone are not considered in the model.

Different mental activities impose different demands on the limited capacity. An easy task demands little effort, and a difficult task demands much. When the supply of attention does not meet the demands, performance falters, or fails entirely. According to the model, an activity can fail, either because there is altogether not enough capacity to meet its demands or because the allocation policy channels available capacity

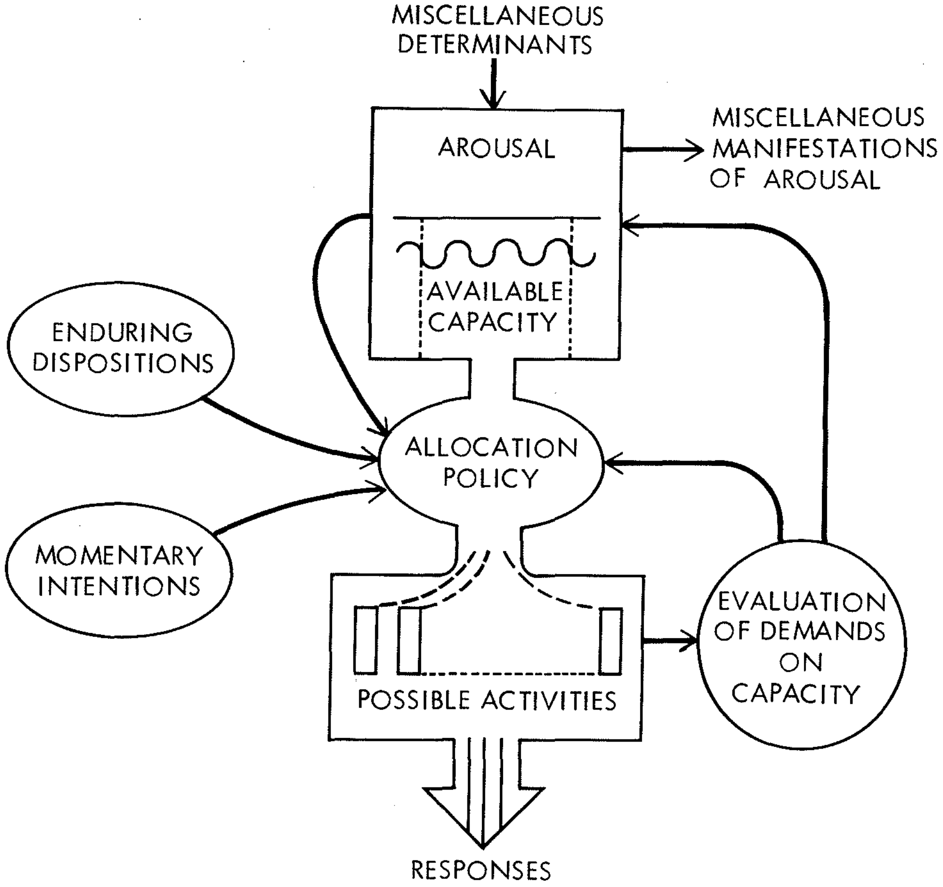

FIGURE 1-2
A capacity model for attention.

to other activities. In addition, of course, an action can fail because the input of relevant information was insufficient. Thus, we may fail to detect or recognize a signal because we were not paying attention to it. But there are signals so faint that no amount of attention can make them plain.

A capacity theory must deal with three central questions: (1) What makes an activity more or less demanding? (2) What factors control the total amount of capacity available at any time? (3) What are the rules of the allocation policy? These questions will be considered in detail in Chapter 2, and occasionally in subsequent chapters. Figure 1-2 merely illustrates some of the interactions between elements of the model that will be used in that analysis.

The key observation that variations of physiological arousal accompany variations of effort shows that the limited capacity and the arousal system must be closely related. In Figure 1-2, a wavy line suggests that capacity and arousal vary together in the low range of arousal levels. In addition, arousal and capacity both increase or decrease according to the changing demands of current activities.

The two central elements of the model are the allocation policy and the evaluation of demands on the limited capacity. The evaluation of demands is the governor system that causes capacity (or effort) to be supplied, as needed by the activities that the allocation policy has selected. The policy itself is controlled by four factors: (1) Enduring dispositions which reflect the rules of involuntary attention (e.g., allocate capacity to any novel signal; to any object in sudden motion; to any conversation in which one's name is mentioned); (2) Momentary intentions (e.g., listen to the voice on the right earphone; look for a redheaded man with a scar); (3) The evaluation of demands: there appears to be a rule that when two activities demand more capacity than is available, one is completed (see Chap. 8); (4) Effects of arousal: systematic changes of allocation policy in high arousal will be discussed in Chapter 3.

The capacity model of Figure 1-2 is intended to complement rather than supersede models of the structure of information-processing such as those illustrated in Figure 1-1. The two figures, in fact, belong to different types: the models of Figure 1-1 are schematic flow-charts that describe the sequence of operations that are applied to a set of simultaneous stimuli. In contrast, Figure 1-2 is a control diagram that describes the relations of influence and control between components of a system. For example, Figure 1-2 implies that a state of overload in which the demands of ongoing activities exceed available capacity will induce a compensatory increase of both arousal and capacity.

The present chapter has illustrated two types of attention theories, which respectively emphasize the structural limitations of the mental system and its capacity limitations. Both types of theory predict that concurrent activities are likely to be mutually interfering, but they ascribe the interference to different causes. In a structural model, interference occurs when the same mechanism is required to carry out two incompatible operations at the same time. In a capacity model, interference occurs when the demands of two activities exceed available capacity. Thus, a structural model implies that interference between tasks is *specific*, and depends on the degree to which the tasks call for the same mechanisms. In a capacity model, interference is *nonspecific*, and it depends only on the demands of both tasks. As Chapters 8 and 10 will show, both types of interference occur. Studies of selective and divided attention indicate that the deployment of attention is more flexible than is expected under the assumption of a structural bottleneck, but it is more constrained than is expected under the assumption of free allocation of capacity. A comprehensive treatment of attention must therefore incorporate considerations of both structure and capacity.

REVIEW AND PREVIEW

The major themes of this book have been outlined in the present chapter. The most important of these themes is an attempt to integrate the intensive and selective aspects of attention. The intensive aspect of attention is identified with effort, and selective attention is viewed as the selective allocation of effort to some mental activities in preference to others. Because of the connection between effort and arousal, physiological measures of arousal can be used to measure the exertion of effort. Some types of information-processing activities can be triggered solely by an input of information. Others require an additional input of attention or effort. Because the total quantity of effort which can be exerted at any one time is limited, concurrent activities which require attention tend to interfere with one another.

A contrast was drawn between a structural model, in which cognitive activity is limited by a bottleneck, or station at which parallel processing is impossible (see Fig. 1-1), and a capacity model in which the limited capacity determines which activities can be carried out together (see Fig. 1-2). Neither model is adequate alone, but each captures some important aspects of cognitive activity.

These major concepts should serve as background for the study of subsequent chapters, which review some central areas of research in attention. Chapters 2 and 3 discuss some intensive aspects of attention and elaborate the capacity model of attention and mental effort. Chapter 4 is devoted to looking behavior. Some variants of selective attention are discussed in Chapter 5, which presents a model of the role of attention in perception. A brief review of attention to attributes in Chapter 6 is followed by a more thorough review of focused and divided attention with simultaneous inputs (Chaps. 7 and 8). The division of attention between simultaneous or immediately successive speeded responses is discussed in Chapter 9. Chapter 10 returns to the concept of effort and its measurement by task interference.

The interested student will find additional relevant material in several recent texts (Broadbent, 1971; Keele, 1973; Moray, 1969a, 1969b; Norman, 1969a). A vast amount of research relevant to attention is conveniently available in special volumes of the journal *Acta Psychologica*, published in 1967, 1969, and 1970. Kornblum (1972) has edited an additional volume in this series. For a humbling look at what was known about attention at the turn of the century, a text by Pillsbury (1908) should be consulted. Woodworth (1938) also reviews much research which remains relevant and interesting, although it is rarely cited in recent work.

2

Toward a Theory of Mental Effort

This chapter elaborates the capacity model that was introduced in Figure 1-2. The first section is concerned with the control of effort by the feedback loop leading from the Evaluation of Demands on Capacity to the Arousal-Capacity system. The second section summarizes the evidence that arousal varies with momentary changes in the load imposed by mental activity. Some determinants of the effort requirements of various activities are discussed in the final section.

THE MOBILIZATION OF EFFORT

The capacity model shown in Figure 1-2 assumed that the capacity which can be allocated to various activities is limited. It also assumed that the limit varies with the level of arousal: more capacity is available when arousal is moderately high than when arousal is low. Finally, it assumed that momentary capacity, attention, or effort (the three terms are interchangeable in this context) is controlled by feedback from the execution of ongoing activities: a rise in the demands of these activities causes an increase in the level of arousal, effort, and attention.

The key observations suggesting this model will be discussed in detail in the next section, where it will be shown that physiological arousal varies second by second when a subject is engaged in a task, and that these variations correspond to momentary changes in the demands imposed by the task. Thus, arousal and effort are usually not determined prior to the action: they vary continuously, depending on the load which is imposed by what one does at any instant of time.

A crude physical analogy may help clarify these ideas. When you push a slice of bread into the toaster, this increases the load on the general electric supply. Without a countervailing change, the new load would cause the voltage supplied to all users to drop. However, the generator that supplies the current is equipped with a governor system which immediately causes more fuel to be burned to restore the constant voltage. In this manner, the total power that the generator supplies varies continuously as a function of the load which is imposed by the momentary choices of the consumers of electricity.

The analogy can be pursued further. Note that, as a user of electric power, you rarely control the amount of power that you require in a continuous or graded fashion. All you decide is that a certain aim is to be achieved, whether it be toasting a bun or illuminating a room. How much power is drawn depends on the structure of the elements that you switch on. As a first approximation, the same rule applies to mental work as well. In general, we merely decide what aims we wish to achieve. The activities in which we then engage determine the effort that we exert.

An important observation in studies of physiological arousal and performance is that arousal varies with the difficulty of different tasks, as measured by error rate. This apparently reasonable finding is actually quite puzzling. At an intermediate level of difficulty, the subject makes a significant number of errors. Yet he does not work as hard as he can, since he exerts greater effort when difficulty is further increased. Why, then, does the subject not work harder at the initial level of difficulty, and avoid all errors?

The answer appears to be that the subject simply cannot try as hard in a relatively easy task as he does when the task becomes more demanding. The reader may wish to confirm this by an armchair experiment. First, try to mentally multiply 83 by 27. Having completed this task, imagine that you are going to be given four numbers, and that your life depends on your ability to retain them for ten seconds. The numbers are seven, two, five, nine. Having completed the second task, it may appear believable that, even to save one's life, one *cannot* work as hard in retaining four digits as one must work to complete a mental multiplication of two-digit numbers.

In an attempt to study this question experimentally, subjects were asked to perform an easy and a relatively difficult task separately, under varying conditions of monetary incentive and risk (Kahneman, Peavler & Onuska, 1968). We did not threaten our subjects' lives but merely rewarded or penalized them ten cents on so-called High-Incentive trials and two-cents on Low-Incentive trials. The diameter of the pupil of the eye was recorded. The incentive had a marginal effect on this manifestation of arousal in the easy task condition, and no effect whatever in the more difficult task. The major determinant of arousal was the difficulty of the task.

This study of incentives is far from conclusive. However, it is consistent with the general hypothesis that the effort invested in a task is mainly determined by the intrinsic demands of the task, and that voluntary control over effort is quite limited. Of course, voluntary control of stop-or-go choices is retained: we can stop working at any time, and often do. How hard we work, when we do, seems to depend primarily on the nature of the activity in which we choose to engage. The tentative conclusion, then, is that the performance of any activity is associated with the allocation of a certain amount of effort. This standard allocation does not yield errorless performance. Allocating less effort than the standard probably will cause a deterioration of performance. Allocating more than the standard seems to be beyond our ability.

Consider again the electrical analogy. In that analogy, the concept of a limited capacity has a precise meaning. The generator can only supply a certain amount of power. When the demands exceed that amount, the addition of one more toaster or air conditioner to the circuit no longer results in a corresponding increase of electrical output. In some systems, overload actually causes the total power supplied by the source to decrease.

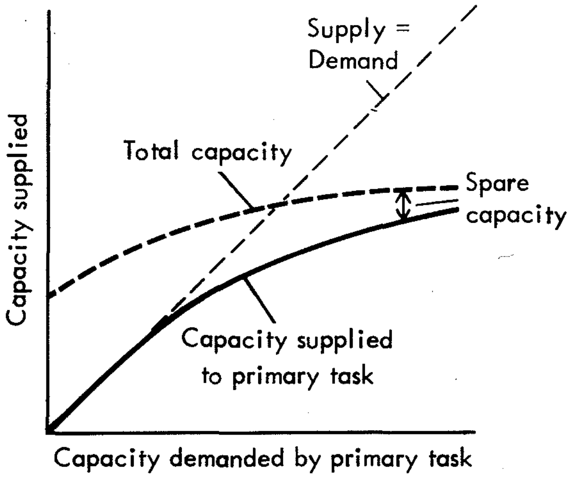

FIGURE 2-1
Supply of effort as a function of demands of a primary task.

A hypothesis concerning the human response to demands on effort is illustrated in Figure 2-1. The illustration refers to a situation in which the subject engages in a particular activity as his primary task. The allocation of effort to that task and the total effort allocated to all activities are shown as a function of the demands of the primary task. Figure 2-1 suggests that capacity (effort) increases steadily with increasing demands of the primary task. However, the increase is insufficient to maintain performance at a constant level of speed and quality. As the demands of the task increase, the discrepancy between the effort demanded and the effort actually supplied increases steadily.

An additional suggestion in Figure 2-1 is that some effort is exerted even when task demands are at zero. The continuous monitoring of our surroundings probably occupies some capacity even in the most relaxed conscious state. This is labeled *spare capacity.* The figure illustrates the hypothesis that spare capacity decreases as the effort invested in the primary task increases: attention is withdrawn from perceptual monitoring and concentrated on the main task. According to a hypothesis stated by Easterbrook (1959), such a change of allocation occurs whenever arousal is high (see pp. 37–42).

A measure of spare capacity can be obtained by studying the response to a probe signal, which is shown to the subject at an unpredictable time during the performance of the primary task (e.g., Kahneman, 1970; Kahneman, Beatty & Pollack, 1967; Posner & Boies, 1971; Posner & Keele, 1968; Posner & Klein, 1972; Shulman & Greenberg, 1971). As will be shown in Chapter 10, a failure to identify a signal that is normally identified with ease or an unusually slow response provides evidence that spare capacity is reduced by task performance. The logic of these methods is that they indicate how much attention was deployed in monitoring at the instant of signal presentation. A failure of attention at that time necessarily causes a slowing of the response, and it may cause a failure to identify a target, if the target is removed before attention can be drawn to it.

Interference between tasks is due to the insufficient response of the system to demands, and to the narrowing of attention when effort is high. Interference will occur even when the total load on the system is far below total capacity. However, the amount of interference is an increasing function of load. At low values of load, the response of the system is approximately linear, and there may be little or no interference between tasks in that region.

It is sometimes assumed that all the capacity of the individual is applied to a primary task, and the occurrence of errors in that task is used as evidence that such is the case (e.g., Shiffrin & Gardner, 1972). The reasoning seems to be that if the individual had more capacity at his disposal, he would surely use it to reduce his error-rate. This view assumes that effort is maximal whenever a well-motivated subject engages in a task in which he makes some errors, regardless of how difficult the task is. In fact, tasks at different levels of complexity elicit different degrees of arousal and demand different amounts of attention and effort.

The present section has elaborated the connection between two elements of the capacity model that was introduced in Figure 1-2: the Evaluation of Demands on Capacity and the Arousal-Capacity system. The main assumption of the model is that the mobilization of effort in a task is controlled by the demands of the task, rather than by the performer's intentions. In addition, the system response is assumed to be insufficient, with an increasing gap between demand and supply when overload is approached. Finally, it is assumed that the spare capacity which is devoted to continuous activities of perceptual monitoring decreases with increasing involvement in a primary task.

THE MEASUREMENT OF EFFORT BY AROUSAL

According to the capacity model introduced in the first chapter, the level of arousal is controlled by two sets of factors: (1) the demands imposed by the activities in which the organism engages, or prepares to engage; and (2) miscellaneous determinants, including the prevailing intensity of stimulation and the physiological effects of drugs or drive states. Thus, as illustrated in Figure 2-2, a state of high arousal may reflect what the subject is doing and the effort he is investing, or it may reflect what is happening to the subject, and the stress to which he is exposed. The fundamental difficulty in the use of physiological techniques to measure effort is caused by the similarity between the physiological responses to mental effort and to stress.

There have been some attempts to identify distinctive physiological concommitants of effort, but the search for such measures has not been very successful. One index that appears promising is a reduction of sinus arrythmia: irregularities of heart rate tend to disappear during the performance of continuous tasks (Kalsbeek & Ettema, 1963, 1964). Porges (1972) reported that subjects who show the greatest reduction of cardiac variability during a task also tend to have the fastest RT's. The reduction of autonomic variability during task performance is apparently a general effect: rhythmic contractions and dilations of the pupil, which are prevalent at rest, are virtually abolished during the performance of mental arithmetic (Kahneman & Beatty, 1966, unpublished observations), and Thackray (1969) has found an inhibition of variability in other measures of autonomic activity during task performance. While promising, these

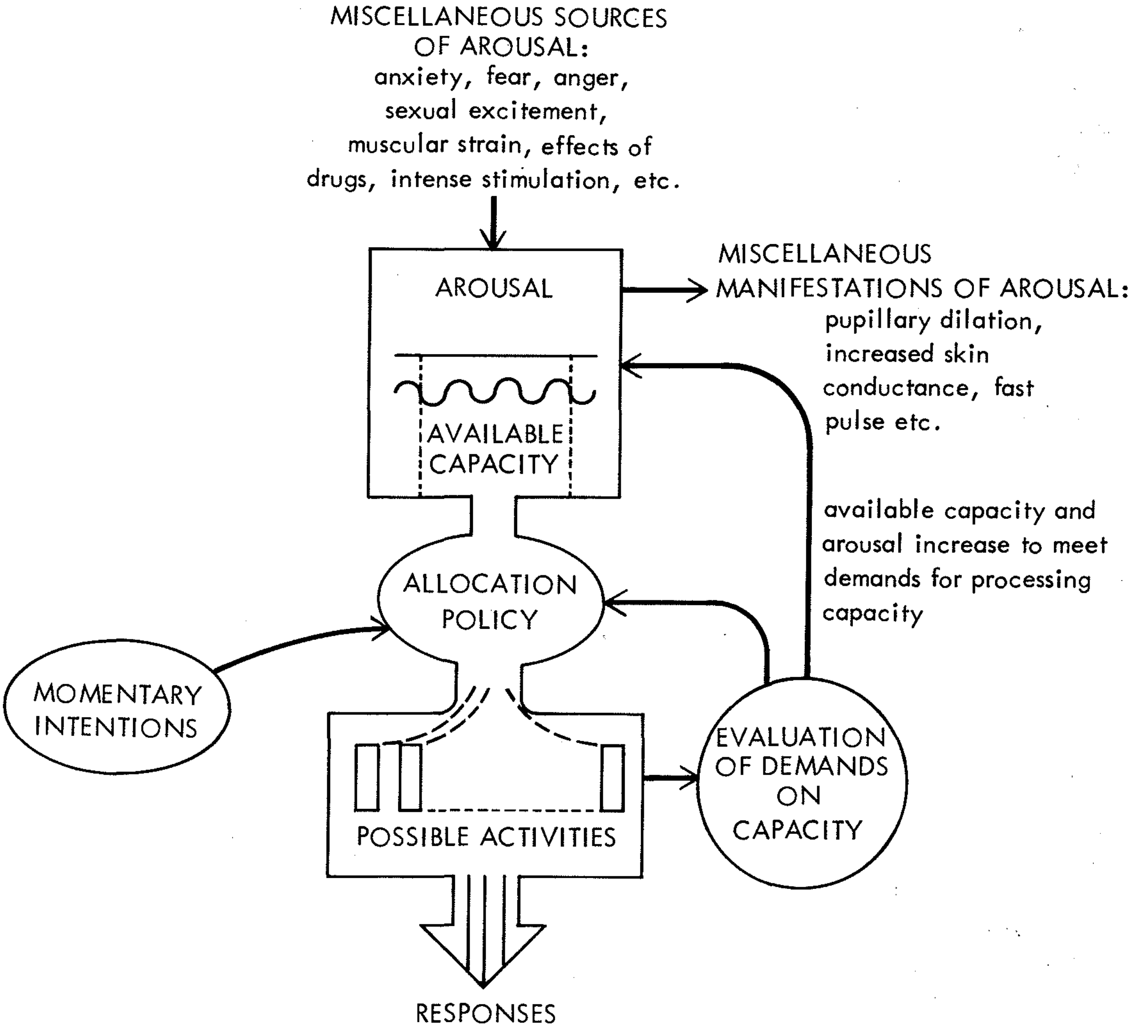

FIGURE 2-2
Effort and other determinants of arousal.

specific measures of effort have had little application, and two standard measures of sympathetic activity remain the most useful autonomic indications of effort: dilation of the pupil is the best single index and an increase of skin conductance provides a related, but less satisfactory measure (Colman & Paivio, 1969; Kahneman, Tursky, Shapiro & Crider, 1969). A third measure of sympathetic dominance, increased heart rate, cannot be used as a measure of effort, for reasons that will be described in Chapter 3.

A useful physiological measure of mental effort must be sensitive to both between-tasks and within-task variations. That is, it should order tasks by their difficulty, since more difficult tasks usually demand greater effort. It should also reflect transient variations of the subject's effort during the performance of a particular task. A perfect measure of mental effort would also reflect between-subject differences, i.e., differences in the amount of effort that different people invest in a given task. There is little evidence concerning the third point (Kahneman & Peavler, 1969; Peavler, 1969), but measurements of pupil diameter appear to meet the first two requirements, and they provide a sensitive indication of both between-tasks and within-task variations of effort (see Goldwater, 1972, for a comprehensive review).

The claim that pupillary dilations indicate mental effort was made by Hess and Polt (1964; Hess, 1965), who observed a striking correspondence between the difficulty of mental arithmetic problems and the magnitude of the dilation during the solution period. The correspondence between cognitive load and pupillary dilation was later confirmed in many contexts: arithmetic (Bradshaw, 1968b; Payne, Perry & Harasymin, 1968); short-term memory tasks of varying load (Kahneman & Beatty, 1966); pitch discriminations of varying difficulties (Kahneman & Beatty, 1967); standard tests of "concentration" (Bradshaw, 1968a); sentence comprehension (Wright & Kahneman, 1971); paired-associate learning (Colman & Paivio, 1970; Kahneman & Peavler, 1969); imagery tasks with abstract and with concrete words (Paivio & Simpson, 1966, 1968; Simpson & Paivio, 1968), and the emission of a freely selected motor response instead of an instructed response (Simpson & Hale, 1969). In all these situations, the amount of dilation increases with task demand or difficulty. The relation between attention and pupillary dilation is maintained even in the absence of specific task instructions: Libby, Lacey, and Lacey (1973) observed dilations of the pupil when the subject merely looked at pictures. The largest dilations occurred while looking at "interesting" and "attention-getting" pictures (see Fig. 3-1 on p. 30). Pratt (1970) also observed that the pupillary dilation varied with the unpredictability of random shapes to which subjects were exposed. Evidently, complex and interesting pictures, like difficult tasks, attract attention and demand a relatively large investment of effort.

The second test of an adequate measure of effort is within-task sensitivity. Several studies have confirmed the suggestion (Hess, 1965) that the size of the pupil at any time during performance reflects the subject's momentary involvement in the task. Indeed, the fidelity of the pupil response permits a second-by-second analysis of task-load and effort. Kahneman and Beatty (1966), for example, showed that the presentation of each successive digit in a short-term memory task is accompanied by a dilation of the pupil. The increase in pupil diameter corresponds to the increasing rate of rehearsal which is imposed by the presentation of the additional digit. This pattern of rehearsal can be altered by presenting the items in several groups, separated by pauses. Then, a brief dilation of the pupil occurs after the presentation of each group, corresponding to the spurt of rehearsal during each pause (Kahneman, Onuska & Wolman, 1968). Finally, when a subject is informed that he need no longer retain the digits he has heard, his pupil briefly dilates, then constricts, as he ceases to rehearse (Johnson, 1971).

The pupillary dilation is a relatively fast response, and major dilations can occur within one second after the presentation of a demanding stimulus. Thus, Beatty and Kahneman (1966) showed that the pupil dilates about 10 percent of base diameter during the first second following the presentation of a familiar name, when the subject must respond by the appropriate telephone number. Similarly, in a pitch discrimination task, the diameter of the pupil reaches a maximum within one second of the presentation of the critical tone; the size of the pupil at that time faithfully reflects the difficulty of the discrimination (Kahneman & Beatty, 1967). When subjects are required to produce an image that corresponds to a particular word, pupil diameter reaches its maximal value faster with concrete than with abstract words (Colman & Paivio, 1969; Paivio & Simpson, 1968; Simpson, Molloy, Hale & Climan, 1968). A plausible explanation of this finding is that the visual image is produced sooner for concrete than for abstract words.

To further test the validity of the pupillary measure of effort, a behavioral measure of spare capacity was introduced. Subjects were required to perform two tasks simultaneously. The primary task involved the transformation of a digit string: the subject heard a series of four digits (e.g., 3916) at a rate of one digit/second, and he was instructed to pause for a second, then to respond with a transform of that series (4027), adding 1 to each digit of the original set. In addition, the subjects performed a secondary task. In one experiment (Kahneman, Beatty & Pollack, 1967), a series of letters was flashed in quick succession, and the subjects monitored the display for the occurrence of a "*K*." In another experiment (Kahneman, 1970), the subjects were briefly shown a single letter, which was to be reported after the completion of the digit-transformation task. The payoff structure in these experiments was designed to ensure priority for the digit-transformation task: the subject was paid for the visual task only if he had performed the transformation task adequately.

Figure 2-3 shows the results of these studies. It includes four curves: (1) a typical pupillary response to the digit-transformation task; (2) the average percentage of missed *K*'s as a function of the time of their presentation; (3) the average percentage of incorrectly reported letters as a function of the time of their presentation; and (4) the average percentage of failures in the digit-transformation task, as a function of the time of presentation of the visual letter.

The most important feature of Figure 2-3 is that the pupillary response and two different behavioral measures of spare capacity show similar trends, although the pupil appears to lag slightly. As a first ap-

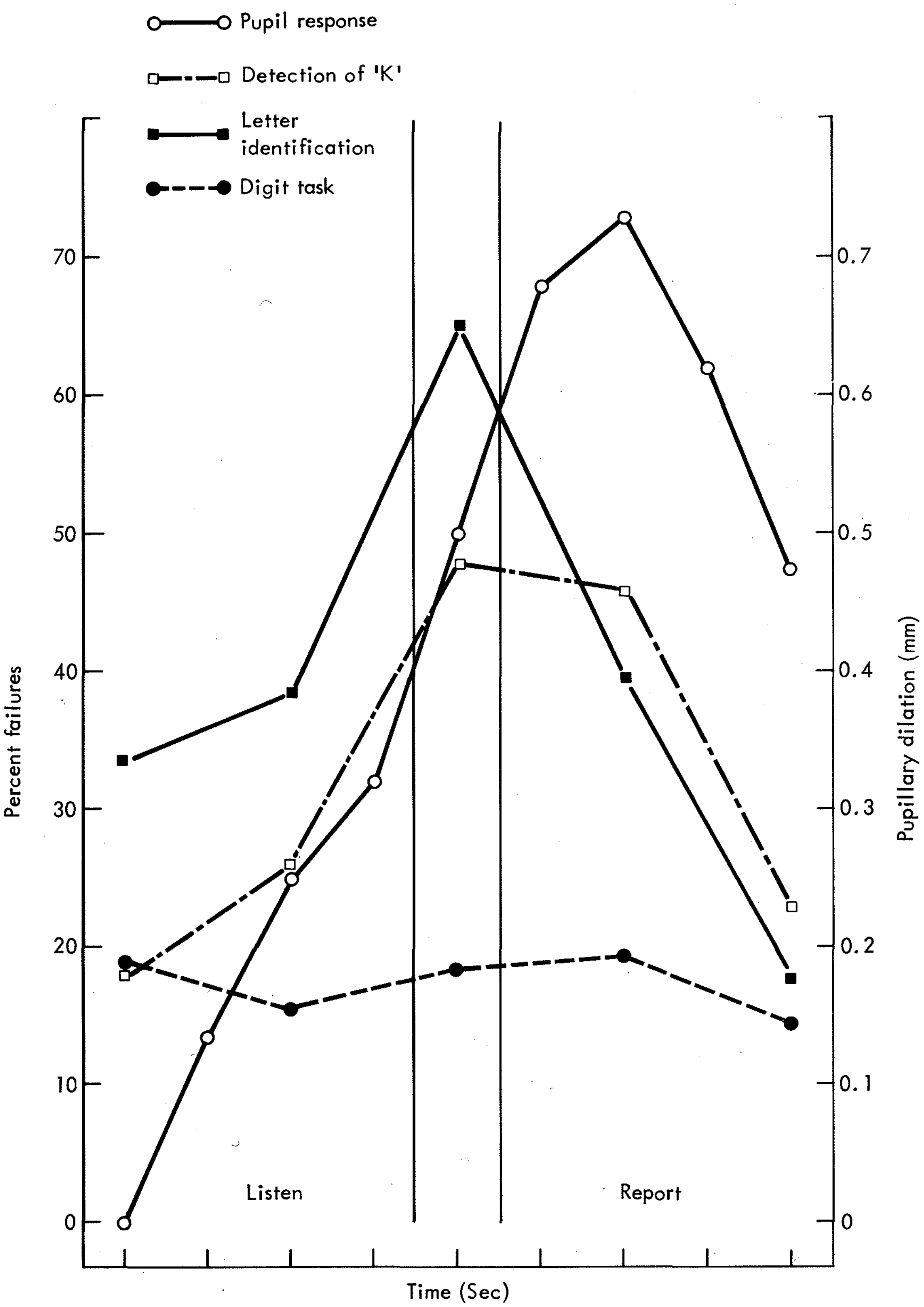

FIGURE 2-3
Two measures of perceptual deficit and the pupillary response to a digit-transformation task. Also shown, the probability of success in the transformation task as a function of the time of occurrence of the visual target. (*Sources:* Kahneman, Beatty & Pollack, 1967; Kahneman, Tursky, Shapiro & Crider, 1969; Kahneman, 1970, with permission).

proximation, a decrement of 10 percent in the likelihood of detecting a *K* is associated with an increase of 0.2 mm in pupil diameter. The decrement of performance is not caused by the dilation of the pupil, however, since similar decrements are observed when the subject sights the target through an artificial pupil. Thus, the physiological and behavioral measures are independent indices of the momentary effort invested in the primary task. Another significant feature is that performance of the primary task appears to be completely independent of the timing of the critical visual event. In the experiments summarized in the figure, a letter that could interfere with the main task was simply not seen, and the performance of the primary task was thereby protected. This strategy, however, is readily altered by modifying the payoffs (Kahneman, 1970). Finally, Figure 2-3 shows that visual performance was severely impaired during the pause between the two parts of the digit-transformation task, a time at which the subject was engaged neither in listening nor in speaking. This observation indicates that mental effort, rather than involvement in either perception or overt response, was the cause of the perceptual deficit. Thus, the results of Figure 2-3 provide support for three central themes of the present chapter: (1) there is a limited capacity for effort, which can be allocated to different tasks; (2) the subject's intentions govern the allocation of this capacity in a highly flexible manner; (3) physiological variables, such as pupil size, provide a useful measure of the momentary exertion of effort.

An additional methodological point should be noted: the pupillary method yields a reliable effort curve of the type illustrated in Figure 2-3 in two or three trials, because the entire response is measured on each occasion. In contrast, dozens of trials are needed to obtain equally reliable results by a behavioral method, in which a single temporal position is probed on each trial.

These demonstrations leave little doubt that pupillary dilations reflect effort. However, much to the chagrin of the student of effort, dilations also occur in other psychological states. As Figure 2-2 indicated, there are many determinants of arousal which all affect autonomic functions in similar ways (Nunally, Knott, Duchnowsky & Parker, 1967). In order to ascribe a particular autonomic change to mental effort, the investigator must therefore assume the burden of proving that this change is not due to such miscellaneous determinants of arousal as muscular strain or anxiety.

Fortunately, the evidence suggests that these contaminating factors play a relatively small part in arousal variations that occur during the performance of mental tasks. The issue of muscular strain arises, for example, whenever a subject must verbalize his responses, but verbalization as such has little effect on the pupil. Figure 2-4 shows the results

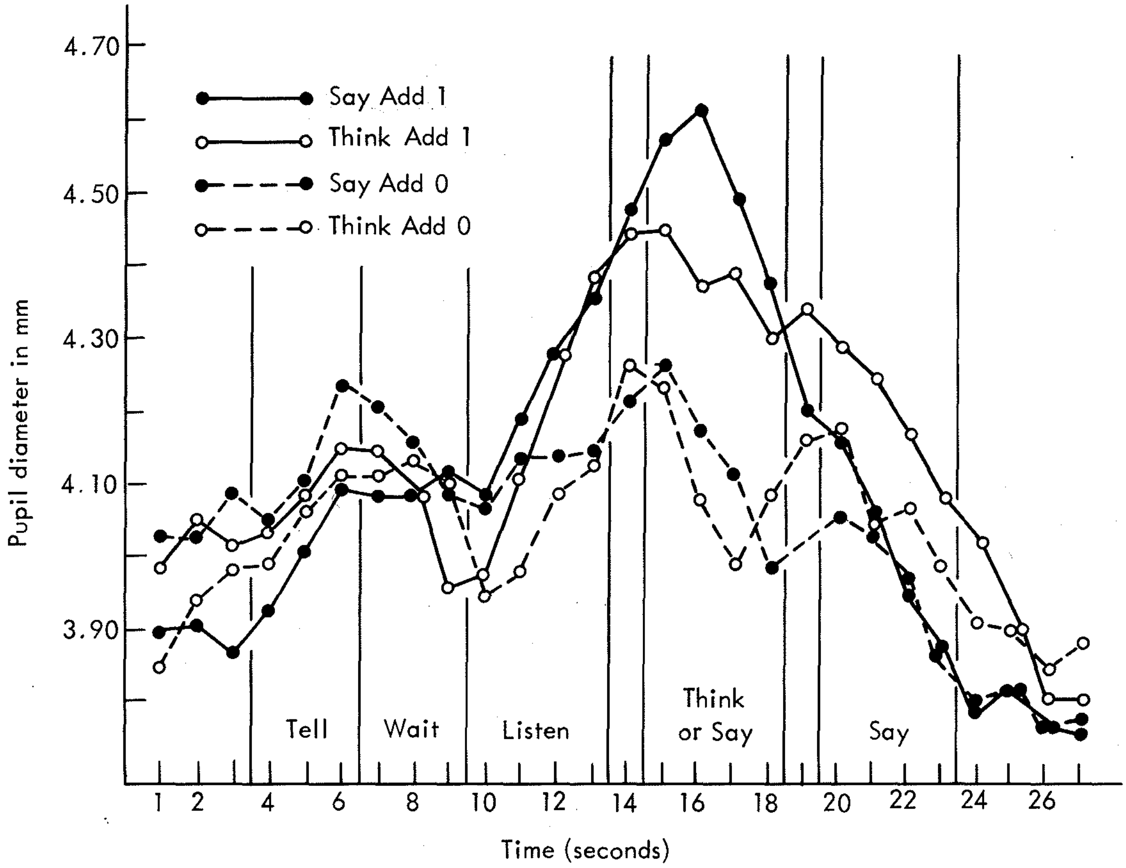

FIGURE 2-4
Pupillary responses to two tasks under instructions to say response twice (say), or to think response and then say it (think). (From Kahneman, Peavler & Onuska, 1968, with permission.)

of an experiment in which subjects heard a string of four digits and were instructed either to repeat the string (Add 0) or to transform the string by adding 1 to each digit (Add 1). In the "Say" condition, they repeated the response twice. In the "Think" condition, they were instructed to "think" their answer first, in time with recorded beats, then to say it. The subjects were given the task instructions (e.g., Say-Add-1) on seconds 4–6 of the trial; then they heard the digits, said or "thought" their answer; and always said the answer on seconds 20–23. The anticipation of the "Say" task caused the pupil to be larger when the presentation of the digits began, and there were other significant effects of verbalization during the task, but these effects were slight in comparison to the effect of task difficulty.

It is often suggested that observed autonomic responses indicate anxiety rather than effort, because it seems reasonable that difficult tasks are associated with high levels of test anxiety. However, this hypothesis would also imply a substantial difference between the conditions of "Think" and "Say" in Figure 2-4, and this was not found. There is other evidence that momentary fluctuations of anxiety play a limited role in determining the pupillary responses in task situations (Kahneman & Peavler, 1969; Kahneman, Peavler & Onuska, 1968; Kahneman & Wright, 1971). Specifically, the anxiety hypothesis would predict a high level of arousal not only at the instant of effort, but also in anticipation of failure and immediately following failure. In fact, the pupil is always largest during the performance of the task, rather than earlier or later. Furthermore, the pupillary dilations which accompany correct responses are often larger than the dilations which accompany failures. Thus, neither muscular strain nor anxiety can account for most of the pupillary changes that occur during mental activity. Nevertheless, the possibility of confounding effects must be cautiously considered in each experiment which relies on measures of arousal to study mental effort (Kahneman & Wright, 1971).

The reader may wish to confirm some of the previous conclusions for himself, and this is easily done. Face a mirror, look at your eyes and invent a mathematical problem, such as 81 times 17. Try to solve the problem and watch your pupil at the same time, a rather difficult exercise in divided attention. After a few attempts, almost everyone is able to observe the pupillary dilation that accompanies mental effort, in a situation which elicits neither overt responses nor test anxiety.

Time-Pressure and Momentary Effort

The studies which validated the pupillary measure of effort usually compared several tasks of the same type, but of different levels of difficulty. Almost invariably, the most difficult version of a task caused the largest pupillary dilation. Among tasks of the same type, it is usually easy to determine a ranking of difficulty by considering the complexity of each task, the speed at which it can be performed, or the probability of failure. It is far more difficult to compare tasks of different types, since neither complexity, speed, nor errors retain a common significance in such comparisons.

The study of pupillary responses, or of other physiological measures of effort, could contribute to such comparisons between tasks of different types and structures. Some rather puzzling results are already available, which must be considered in a theory of effort. In studies of paired-associate learning, for example, the dilation which occurs when the subject's recall is tested may be four to six times as large as the dilation which occurs when the subject attempts to memorize an item (Kahneman & Peavler, 1969). Can it be inferred that learning requires much less effort than recall? Large pupillary responses accompany other tasks that could be considered "easy," such as the prompted recall of thoroughly overlearned information: one's telephone number or one's age (Beatty & Kahneman, 1966; Schaefer, Ferguson, Klein & Rawson, 1968). Similarly, retaining five digits for immediate recall is considered easy, since it is a task in which we rarely fail. Nevertheless, larger dilations occur in this simple task than in an apparently more complex task, where subjects are required to listen to a long message and comprehend it (Carver, 1971).

It is apparent from these observations that the intuitive notion of task difficulty is not sufficient to determine the amount of effort that a task demands. The problem arises at least in part because of the vagueness of the notion of difficulty. Thus, difficulty is often identified with the likelihood of error. By this definition, retaining nine digits in a test of short-term memory is extraordinarily difficult. By the same definition, crossing out every letter A in this book is also very difficult, since a few will almost certainly be missed. However, retaining nine digits and crossing out A's impose different demands at any instant in time.

The *momentary* effort that a task demands must be distinguished from the total amount of work that is required to complete that task. The momentary effort exerted in running the 60-yard dash is greater than the effort exerted in walking two miles at a comfortable pace, although the total expenditure of energy is surely greater in the second task. In the terms of this analogy, much of our mental life appears to be carried out at the pace of a very sedate walk. When one reads a book or listens to a lecture, for example, effort is minimal because the material is not actively rehearsed, and because the redundancy of the message reduces any sense of time-pressure.

Furthermore, the amount of genuinely new information acquired per unit time in such situations is probably small. Murdock (1960) estimated that subjects presented with a long list of unrelated words transfer information into long-term memory at the strikingly slow rate of 3.6 words/minute. Memory for connected discourse appears to be better only because of the effects of prior knowledge and redundancy. Thus, it is not inconceivable that continuous mental activities, such as reading, tax our capacity only rarely. We cover great distances by such mental walking, with only minimal effort.

This conception of mental work suggests that *time-pressure* must be an important determinant of effort. This is a familiar idea in the context of physical exertion: anyone who has tried jogging knows that even a small increase of speed beyond the relatively effortless "natural" speed causes a disproportionate increase in the sense of strain.

Time-pressure is often involved in mental tasks. It is sometimes imposed by explicit instructions to hurry and sometimes by demand characteristics of the task. For example, Simpson and Paivio (1966, 1968) asked subjects to produce images to words, and they observed particularly large pupillary dilations when the subject was also asked to indicate the instant at which he achieved the image. Since the occurrence of an overt response is neither a necessary nor a sufficient condition for large pupillary dilations, it seems likely that the instruction to report the achievement of an image induced time-pressure, and thereby increased effort.

The most important type of time-pressure is that which is inherent in the structure of the task. Thus, severe time-pressure necessarily arises in any task which imposes a significant load on short-term memory, because the subject's rate of activity must be paced by the rate of decay of the stored elements. In mental arithmetic, for instance, one must keep track of the initial problem, of partial results already obtained, and of the next step. Stopping or slowing even for an instant usually forces one to return to the beginning and start again. In tests of short-term recall, the increasing number of items that must be rehearsed causes a rapid buildup of time-pressure, which is also reflected in autonomic measures of arousal. Time is also critical in a pitch-discrimination task with brief tones, where rapidly decaying traces must be quickly evaluated. In all these tasks, large pupillary dilations occur.

Some problems are difficult because the elements that are essential to the solution are relatively inaccessible to retrieval from memory. Other problems are difficult because they impose severe time-pressure. The indications are that effort is less closely related to the dimension of accessibility than to the dimension of time-pressure. During paired-associate learning, for example, the pupillary response at recall decreases quite slowly with increasing familiarity (Kahneman & Beatty, unpublished observations). Bradshaw (1968b) has reported that the size of pupillary dilations does not vary with the difficulty of word-construction problems, although it varies consistently with the difficulty of arithmetic problems. The difference could be due to the differing roles of storage and rehearsal in the two tasks. The more difficult arithmetic problems require more storage and rehearsal than do easier problems, and therefore impose more time-pressure. In contrast, a word problem is difficult only because correct answers are few and inaccessible; it imposes neither more load on storage nor more time-pressure than an easy problem, and it does not elicit greater effort.

REVIEW

The approach to the concept of effort that was developed in this chapter assumes that effort is mobilized in response to the changing demands of the tasks in which one engages, and that there is a standard allocation of effort for each task. The investment of less than this standard effort causes a deterioration of performance, but in most tasks it is impossible to completely eliminate errors by a voluntary increase of effort beyond the standard. As a result, the voluntary control of effort is limited in scope. It was assumed that the increased allocation of effort to difficult tasks does not suffice to maintain performance at a constant level, and that the spare capacity that remains available for perceptual monitoring decreases with increasing involvement in a primary task.

Evidence was presented that transient variations of arousal during the performance of a mental task correspond to transient changes in the demands of the task and to temporary decrements in behavioral measures of spare capacity. However, the measurement of effort by physiological indications of arousal such as the pupillary dilation is complicated by the fact that the manifestations of arousal are not specific to effort.

Finally, the concept of momentary effort was distinguished from the probability of failure in a task and from the total amount of work required by that task. Much mental activity appears to occur without the exertion of substantial effort. Time-pressure is a particularly important determinant of momentary effort. Tasks that impose a heavy load on short-term memory necessarily impose severe time-pressure.

3

Arousal and Attention

The first section of this chapter describes the autonomic manifestations of two attentional states: a state of motor activation and active manipulation of information, and a state of acceptance of sensory information and inhibition of response. Subsequent sections are devoted to the Yerkes-Dodson law, which describes the effects of arousal on performance, and to Easterbrook's hypothesis that high arousal causes an alteration in the allocation of attention. The final section describes the orientation reaction, which comprises some aspects of the involuntary allocation of attention to novel stimuli.

VARIANTS OF HIGH AROUSAL

In the preceding chapters, the concept of arousal was treated as a unitary dimension, as if a subject's arousal state could be completely specified by a single measurement such as the size of his pupil. This, however, is an oversimplification. Although the idea of a dimension of general arousal is useful, some important qualifications must be considered. As this section will show, there are at least two distinctively different states of high arousal.

Manifestations of sympathetic dominance have traditionally been used to identify arousal level. Indeed, pulse rate, pupil diameter, and skin conductance usually increase in arousing conditions. However, Lacey (1959, 1967) has pointed out that the concept of a unitary dimension of arousal implies that the correlations among these measures should be high: if an individual is more aroused in one situation than in another, all indices of sympathetic dominance should reflect this fact. The observed correlations, however, are often quite low. Furthermore, systematic discrepancies between measures occur under different types of stress: different stressors elicit different patterns of autonomic activity, as well as different degrees of sympathetic dominance.

In some situations, one autonomic variable may indicate sympathetic dominance even as another variable displays a typical parasympathetic response. Lacey (1967) has coined the term *directional fractionation* for such discrepant patterns.

An important instance of directional fractionation was first described by Davis (1957). He observed conditions in which most indices of sympathetic dominance rose while the pulse slowed down. Davis found it easy to produce this response, which he labeled the P-pattern, by showing male students pictures of female nudes, but the effect is not restricted to such stimuli. Thus, the presentation of visual stimuli to infants also causes a very marked cardiac deceleration, which is sufficiently reliable to provide a useful index of attention (Kagan, 1972; Kagan & Lewis, 1965; Lewis, Kagan, Campbell & Kalafat, 1966; Lewis & Spaulding, 1967).

Figure 3-1 illustrates directional fractionation in a study by Libby, Lacey, and Lacey (1973). They allowed subjects to look at 30 pictures for 15 seconds each, without any specific task instruction. The figure shows pupillary and cardiac responses for pictures rated low, medium, or high on a factor of Attention-Interest. Directional fractionation is clearly evident, since pupil size increases while the heart slows. Furthermore, the amount of fractionation depends on how interesting the pictures are: the largest dilations and the lowest pulse are obtained for the most interesting pictures.

In more complex tasks, directional fractionation occurs if the subject is allowed to passively observe the stimuli. Lacey, Kagan, Lacey, and Moss (1963) measured cardiac responses of subjects in a series of one-minute tasks. They found deceleration and directional fractionation in tasks of passive observation, and generalized sympathetic-like responses in problem-solving tasks. Intermediate results were obtained when both task components were involved.

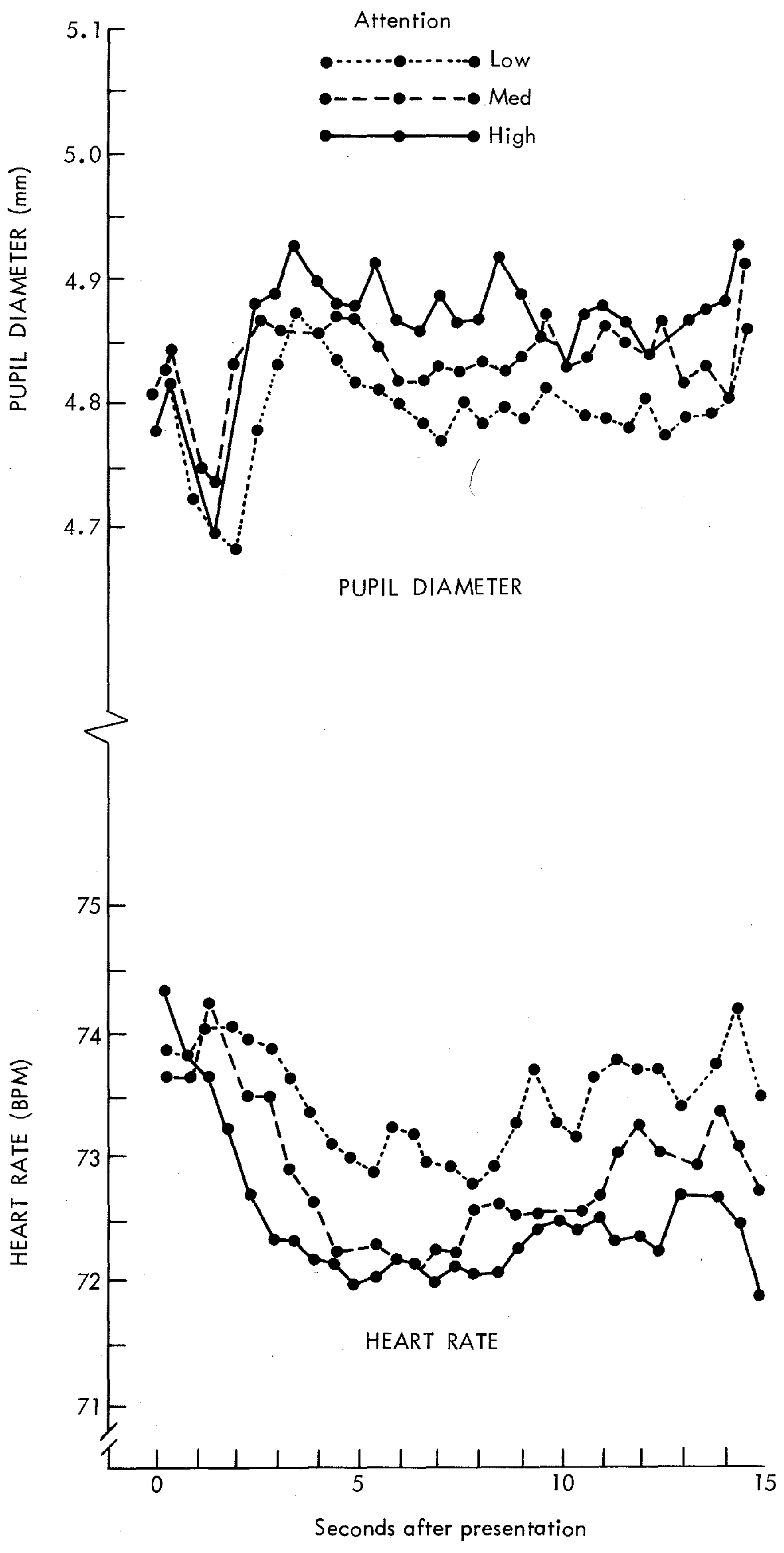

FIGURE 3-1
Cardiac and pupillary responses to pictorial stimuli at three attention values (adapted from Libby, Lacey & Lacey, 1973, with permission).

Directional fractionation occurs when the subject is merely exposed to information, but it is replaced by the common arousal pattern when the subject starts to manipulate the information in a task. Thus, Tursky, Schwartz, and Crider (1970) asked subjects to listen to a string of four digits and to subsequently report a transform of this list (Add 1). While the subject was listening to the digits, there was a marked cardiac deceleration accompanied by a rise in skin conductance. Later, the heart accelerated as the subject prepared and rehearsed his response.

Lacey (1967) proposed that generalized sympathetic dominance occurs when the individual resists stimulation, either because it is aversive (e.g., continuous pain) or because it is distracting (e.g., stimulation that interrupts problem-solving activity). He suggested that directional fractionation with cardiac deceleration occurs in states of attentive acceptance of external stimulation, and that heart rate plays a causal role in a feedback loop which controls attention.

While the existence of directional fractionation is not in doubt, Lacey's original interpretation of acceleration as a correlate of stimulus-rejection was probably incorrect. In the data of Libby, Lacey, and Lacey (1973), for example, the largest cardiac decelerations were observed for the most unpleasant stimuli. The evidence supports an alternative formulation, that momentary heart rate reflects the current degree of motor tension or mobilization for action.

Directional fractionation and cardiac deceleration reliably occur under conditions of "waiting for something to happen." The two waiting situations that have been investigated most thoroughly are: (1) the foreperiod between an alerting signal and the stimulus in a reaction-time experiment (Chase, Graham & Graham, 1968; Connor & Lang, 1969; Coquery & Lacey, 1966; Lacey & Lacey, 1964, 1966; Obrist, Webb & Sutterer, 1969; Obrist, Webb, Sutterer & Howard, 1970b; Webb & Obrist, 1970); and (2) the interval between a neutral conditioned stimulus (CS) and an aversive unconditioned stimulus (UCS) in a classical conditioning paradigm (Deane, 1961; Hastings & Obrist, 1967; Jenks & Deane, 1963; Notterman, Schoenfeld & Bersh, 1952; Obrist, 1968; Obrist, Wood & Perez-Reyes, 1965; Wilson, 1964).

The waiting paradigm has been studied carefully by Obrist, who found that cardiac deceleration is typically accompanied by a marked reduction of irrelevant movement, and by the steady fixation of an unblinking eye (Obrist, Webb & Sutterer, 1969; Webb & Obrist, 1970). This pattern is adaptive: any subject in a reaction-time experiment soon discovers that a high level of motor tension during the foreperiod yields a slow RT. A relatively relaxed posture, in which ongoing activity is inhibited, tends to be optimal. Indeed, Obrist, Webb, Sutterer, and Howard (1970b) confirmed the correlation between inhibition of irrelevant activity and the subsequent RT. They also found that the correlation is maintained even when the cardiac deceleration is prevented by atropine, a result which provides decisive evidence against Lacey's suggestion that cardiac deceleration plays a causal role in the control of attentional patterns. Rather, the decrease in heart rate is simply a manifestation of a general inhibition pattern. A detailed discussion of the physiological mechanisms controlling the cardiac response has been offered by Obrist, Webb, Sutterer, and Howard (1970a). Further evidence for Obrist's analysis was offered by Cohen and Johnson (1971), who observed highly significant correlations between heart rate and electromyographic measures of muscle tension, both within each subject's data (over successive measurements) and between subjects: the most relaxed subjects had the slowest pulse.

The inhibition of movement during the RT foreperiod has correlates in the measurable activity of the brain. The alerting stimulus of the RT paradigm is normally followed by a very consistent change in the EEG, known as the CNV, or contingent negative variation (Walter, Cooper, Aldridge, McCallum & Winter, 1964). The CNV, sometimes called the expectancy wave, is a sustained change of baseline potential which is contingent upon the expectation of a subsequent significant stimulus (Cohen, 1969; Tecce, 1972). The occurrence of a CNV tends to be associated with a slow heart rate during the foreperiod, and with a fast RT (Connor & Lang, 1969; Hillyard, 1969).

Elliott (1969) observed directional fractionation in a new and rather unexpected situation, and he proposed an interpretation of the cardiac response which was quite similar to Obrist's view. He studied autonomic responses in the conflict situation induced by the Stroop test, in which the subject must read the colors in which color names are printed and refrain from reading the words themselves (see p. 109). In this conflict situation the subject may be noticed "reading . . . with almost emphatically deliberate pace, holding himself back from a speed that might produce confusion and error [Elliott, 1969, p. 218]." This inhibitory pattern is accompanied by a slowing of the heart. Elliott concluded that cardiac deceleration is associated with the inhibition of responses, and that cardiac acceleration accompanies the instigation, anticipation, and initiation of responses. In a further test of this hypothesis, Elliott, Bankart, and Light (1970) measured heart rate and palmar conductance for the three conditions of the Stroop test (word, color, and word-color interference) and found that heart rate fell as the difficulty of the test condition increased, while palmar conductance rose.

In conclusion, consideration of the cardiac response and of the nature of the task situation permits two, and perhaps three states of high arousal to be distinguished:

(*1*) A pattern of motor inhibition. The state of generalized *alertness* which is induced by a warning signal (Posner & Boies, 1971) probably consists of a combination of inhibition and increased arousal. The inhibition serves to clear the system for an anticipated stimulus (e.g., the foreperiod situation), or to cope with potentially disruptive response conflict (e.g., the Stroop test). Elliott's observations with the Stroop test show that an inhibitory *tendency* is sufficient to cause cardiac slowing, even while the subject is verbalizing and showing considerable evidence of motor tension (for further detail on this point, see p. 109).

(2) A pattern of relaxed acceptance of external stimulation. Whether this pattern must be distinguished from the first is currently not clear.

(3) The standard pattern of generalized sympathetic dominance, which invariably occurs both in situations of physical strain or effort and in problem-solving. In these situations, a *tendency* toward verbalization and motor response is sufficient to cause a cardiac acceleration. Thus, a pronounced cardiac acceleration may occur while a subject attends to an external source of stimulation, if he is engaged in preparing a verbal response (Campos & Johnson, 1966, 1967; Johnson & Campos, 1967).

The evidence of this section disproves the early idea that arousal can be identified with sympathetic dominance. Subtypes of arousal must be distinguished. However, the suggestion that the concept of arousal should be abandoned appears too extreme. A concept of arousal is needed to differentiate the state of the subject in a task situation from his state at rest. While solving a problem, looking at a picture, or reading a Stroop card, the subject is more active and alert, in short more aroused, than he is at rest. Arousal can be measured, since there are at least two indices of autonomic activity, skin conductance and pupil size, which appear to increase monotonically with attention in all task situations.

THE YERKES-DODSON LAW AND THE EFFECTS OF NOISE ON PERFORMANCE

The capacity model introduced in Chapter 2 indicated a mutual relation between attention and arousal. Variations of attention demands cause corresponding variations of arousal, but variations of arousal also affect the policy by which attention is allocated to different activities. The fundamental law that relates performance to arousal is the Yerkes-Dodson law, which states that the quality of performance on any task is an inverted U-shaped function of arousal, and that the range over which performance improves with increasing arousal varies with task complexity (Yerkes & Dodson, 1908). These relations are schematically illustrated in Figure 3-2.

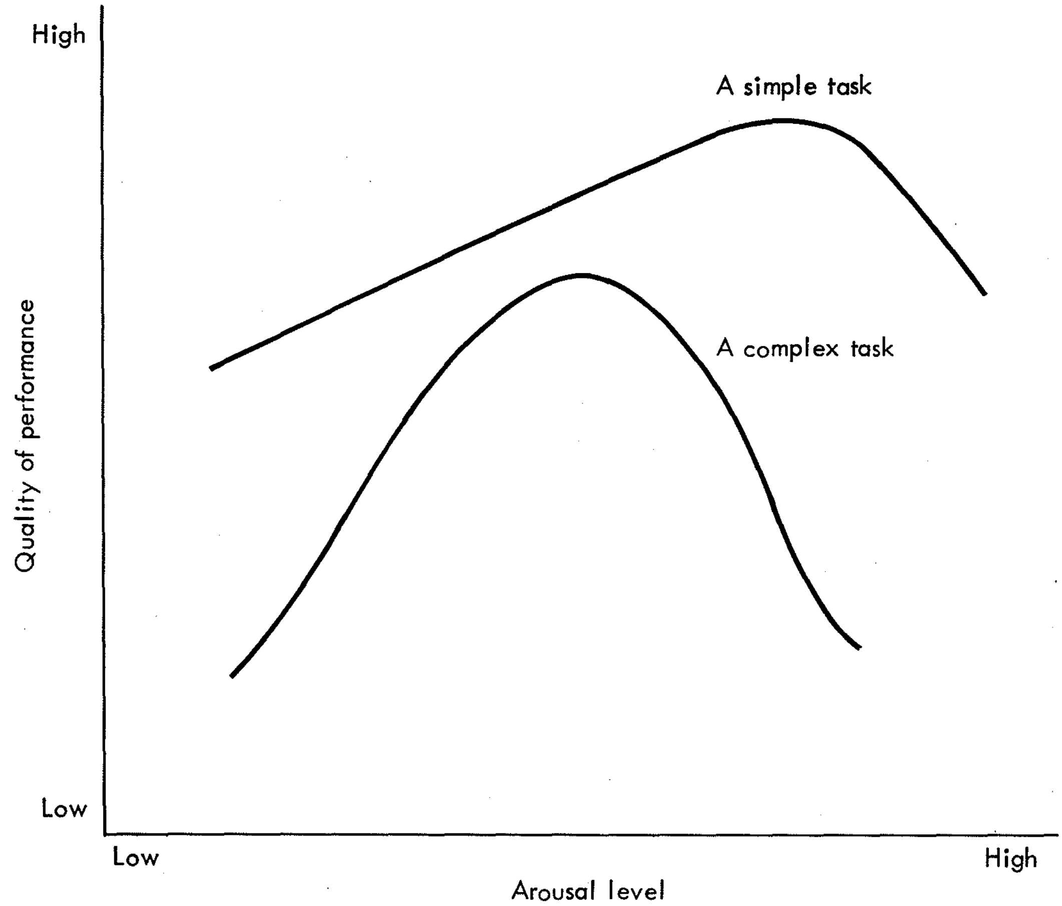

FIGURE 3-2
The Yerkes-Dodson law.

The Yerkes-Dodson law was initially formulated in the context of animal discrimination learning. Yerkes and Dodson discovered that increasing the intensity of a shock administered to mice facilitated the learning of a brightness discrimination, up to a point. Further increases of shock intensity caused learning to deteriorate. Yerkes and Dodson also discovered that the effects of shock were more pronounced in difficult discriminations, and that the optimum level of shock was higher in easy discriminations. These conclusions, initially drawn from a crude experiment with a few dozen mice, appear to be valid in an extraordinarily wide range of situations (Broadhurst, 1957, 1959; Duffy, 1957; Malmo, 1959; Schlosberg, 1954; Stennett, 1957).

An interesting application of the Yerkes-Dodson law concerns the effects of loud background noise on human performance (Hockey, 1969, 1970a). Generally, this type of distraction is resisted very well (Broadbent, 1957b, 1958), but long periods of exposure to noise do affect performance in several ways. Continuous noise increases arousal level (Davies, 1968; Hockey, 1969), and the effects on performance of this increase of arousal depend on the nature of the task, as predicted by the Yerkes-Dodson law. In general, the presentation of loud background noise causes an improvement in the performance of easy tasks and a deterioration when the tasks are more complex (Boggs & Simon, 1968; Broadbent, 1954b; Hockey, 1970a; Houston, 1968). This conclusion is consistent with the hypotheses represented in Figure 3-2.

The Yerkes-Dodson law provides an elegant explanation for cases in which the effects of concurrent stresses appear to be non-additive. For example, both loud background noise and lack of sleep are detrimental to performance in a complex serial-reaction task, but the combination of the two stresses, lack of sleep *and* loud noise, is less detrimental than lack of sleep alone. On the other hand, the detrimental effects of loud noise are aggravated by giving the subject full knowledge of results (KR) concerning the quality of his performance, although KR alone normally improves performance (Wilkinson, 1963). The results are explained by assuming that both loud noise and knowledge of results increase arousal, and that together they raise it excessively.

The Yerkes-Dodson law also explains some puzzling differences in the response to noise stress shown by introverts and extroverts. Although extroverts are more lively than introverts, research evidence suggests that they are chronically *less* aroused (Corcoran, 1965; Eysenck, 1967). Correspondingly, the gradual deterioration of performance in continuous watch-keeping, called the vigilance decrement, is normally more severe for extroverts than for introverts (Bakan, Belton & Toth, 1963; Broadbent, 1963). As may be expected from this analysis, extroverts engaged in a watch-keeping task benefit more from the presentation of noise than do introverts (Davies & Hockey, 1966; Davies, Hockey & Taylor, 1969). Presumably, the arousal level of extroverts tends to be suboptimal, and it is restored by the presentation of noise.

The results discussed in this section are interpretable within a capacity model. Figure 3-3 includes the elements of that model which are relevant to the Yerkes-Dodson law. The figure suggests that the detrimental effects of low and high arousal are due to different mechanisms.

The failure of the under-aroused subject is most easily explained by assuming that the effort exerted in the task is insufficient. Why is this so? The answer is surely not that arousal cannot increase to meet task demands: perhaps the most striking conclusion of research on sleep deprivation is that the sleepless subject, normally under-aroused, can perform almost any task at a normal level when highly motivated (Wilkinson, 1962, 1965). Indeed, sleepless and fatigued individuals who must nevertheless perform a task show evidence of high physiological arousal

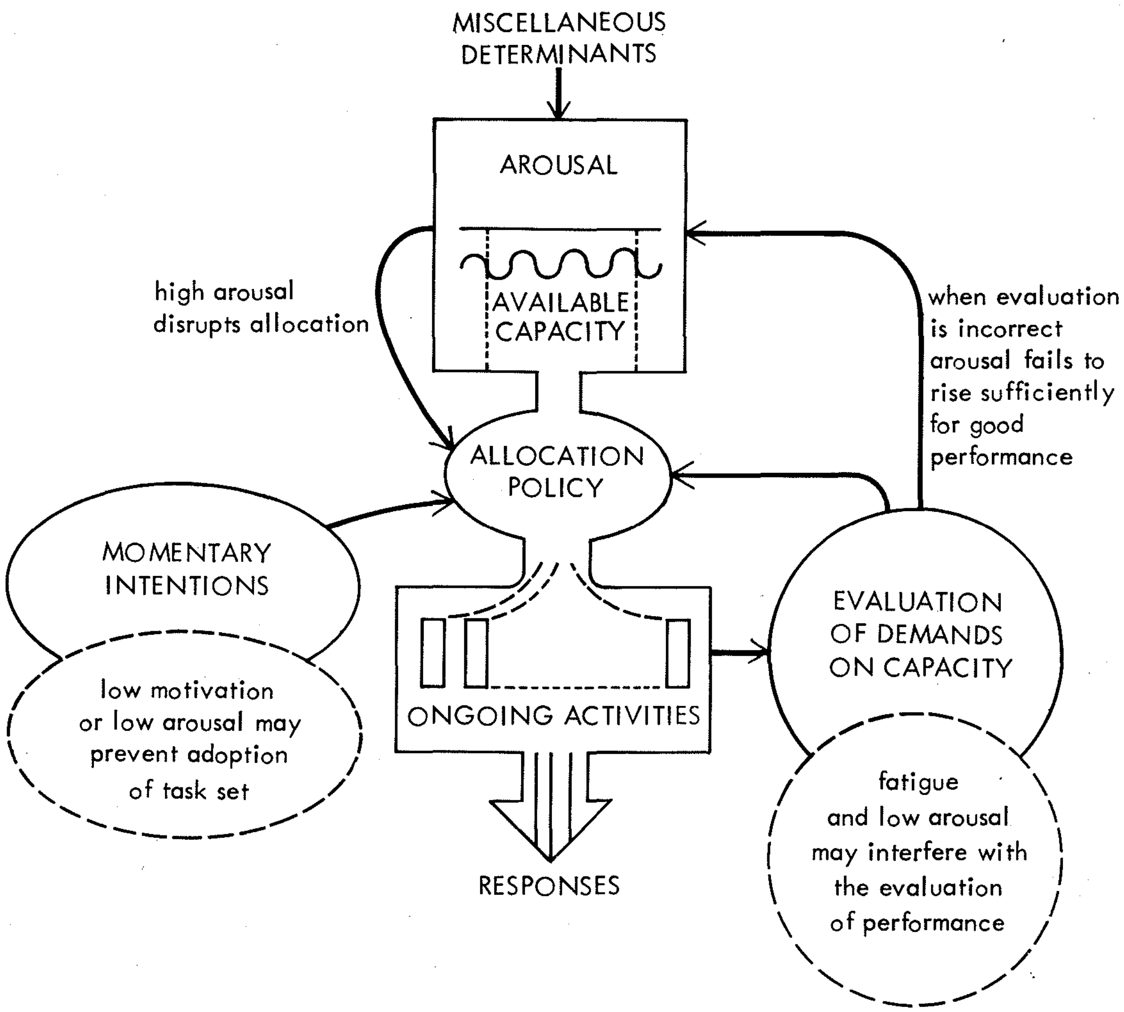

FIGURE 3-3
Effects of high and low arousal on attention and performance.

(Malmo, 1965; Malmo & Surwillo, 1960). Fatigue and sleep deprivation apparently increase the difficulty of continuous performance, and the motivated subject compensates for the added difficulty by increasing his effort.

In general, then, if an initially drowsy person is given a task, he will wake up and perform. In the terms of an effort model, it may be more accurate to say that the person will perform and wake up, since it is the demand of the performance that causes the increase of arousal and of capacity. The occasional failures of this feedback system are best explained by motivational factors (Broadbent, 1971). The fatigued or sleepy subject may (1) fail to adopt a task set; or (2) fail to evaluate the quality of his own performance. Figure 3-3 indicates that, if failures in a task are not detected, the system will reach equilibrium at low levels of both arousal and performance. A motivational interpretation explains both the dramatic effect of knowledge of results (KR) on the performance of sleep-deprived subjects (Wilkinson, 1961, 1963), and the original

Yerkes-Dodson discovery that the speed of discrimination learning depends on the intensity of the stress that motivates learning.

The detrimental effects of over-arousal must be explained in other terms, however. The allocation of capacity appears to change systematically when arousal is high, and this change causes a decrement in the performance of certain tasks. The next section reviews the evidence for this conclusion.

EFFECTS OF AROUSAL ON ALLOCATION POLICY

Easterbrook (1959) presented a theory which was intended to explain both the decrement of task performance with increasing arousal, and the observation that this decrement occurs sooner in complex tasks than in simple ones. He proposed that an increase of arousal causes a restriction of the range of cues that the organism uses in the guidance of action.

This hypothesis explains the Yerkes-Dodson law as follows: consider a task which requires the simultaneous processing of a certain number of cues. When arousal is low, selectivity is also low, and irrelevant cues are accepted uncritically. When arousal increases, selectivity increases also, and performance improves because irrelevant cues are more likely to be rejected. With further increases of arousal, however, the continuing restriction of the range of usable cues eventually causes relevant cues to be ignored, and performance deteriorates again, in accordance with the Yerkes-Dodson law. With the additional assumption that the range of necessary cues is narrower for simple than for complex tasks, this argument implies that the optimal level of arousal should be relatively high in simple tasks. It also implies that chronically over-aroused individuals should perform poorly in complex tasks and relatively better in simple tasks. There is considerable evidence that both conclusions are valid.

Easterbrook marshalled much research support for the narrowing of attention under high arousal. For example, he cited an experiment by Bahrick, Fitts, and Rankin (1952) in which subjects were engaged in two tasks: continuous tracking of a target, and monitoring the occurrence of occasional signals in the visual periphery. When the incentive pay for both tasks was increased, performance of the central task improved, and performance of the peripheral task deteriorated. Similar findings were also described by Bursill (1958), who manipulated arousal by making his subjects work under conditions of extreme heat and humidity. The balance of attention to central and peripheral tasks was altered in conditions of high arousal.

Related results have been reported by Callaway (1959; Callaway & Stone, 1960; Callaway & Thompson, 1953), who manipulated arousal by means of drugs. He concluded that atropine, which decreases arousal, tended to improve the registration of peripheral cues, whereas amphetamine had the opposite effect.

The results of these studies do not imply that peripheral vision is impaired by drugs, stress, or incentives. What happens in high arousal is a change in the rules of allocation of attention and effort. Thus, Bursill (1958) noted that the decrement of peripheral detection in high arousal did not occur when the peripheral task was emphasized. Cornsweet (1969) also found that peripheral vision was unimpaired when the competition between peripheral and central tasks was removed. Indeed, she found that a peripheral cue anticipating a central signal was used more effectively when the central signal was associated with shock (high arousal) than when it was not (low arousal). In a dual task situation similar to Bursill's, Hockey (1970c) observed that the relative preference for central targets is reduced under sleep deprivation (i.e., low arousal) and enhanced under noise stress (Hockey, 1970a). However, he was able to show that the neglect of peripheral targets under stress is due to the low probability of detecting such targets, which reduces their importance (Hockey, 1970b). In the terms introduced earlier, the detection of rare events in the presence of a primary task depends on the allocation of spare capacity to perceptual monitoring, which diminishes when effort and arousal increase.

This research demonstrates that high arousal causes attention to be concentrated on the dominant aspects of the situation at the expense of other aspects. As Easterbrook noted, such a change of allocation policy will disrupt any performance in which attention must be deployed over a wide range of cues. Complex tasks often require attention to varied cues, and are therefore performed poorly when arousal is high.

High arousal apparently causes an *increased tendency* to focus on a few relevant cues. However, the selection of relevant cues often involves a discrimination between these cues and others. A state of high arousal tends to impair such discriminations, with a consequently *reduced ability* to focus on the relevant cues. Thus, although subjects spontaneously become more selective when highly aroused, the effectiveness of their selections is likely to deteriorate, if the selection requires a fine discrimination.

Broadbent (1971, p. 430) has studied selective attention in high arousal. In one experiment his subjects were shown tachistoscopic exposures of word pairs, with one word in heavy print and the other less visible. On different trials the subject was required to identify one or the other of these words, and the duration of exposure was gradually increased until he could do so. The task was performed both in quiet and under intense continuous noise. The noise had a slight beneficial effect on the detection of the heavily printed word. Of course, when that word was at threshold, the more finely printed word paired with it was hardly visible. When the subject was required to identify the less visible word, however, the word in heavy print must have been clear and obvious. The "pull" of that stimulus was apparently harder to resist in noise than in quiet, because the identification of the faint word was significantly impaired by the presence of noise.

Another experiment reported by Broadbent (1971, p. 430) also suggests that the ability to select relevant stimuli is impaired by arousal. Subjects were briefly shown an array of red and white digits and were asked to report as many digits of one specified color as they could. Performance in this selective task deteriorated under loud noise. In contrast, noise was associated with a slight performance improvement when subjects were told to write as many digits as possible, regardless of color.

In contrast to the impairment of effective selection in Broadbent's experiments, there are situations in which selective attention to relevant stimuli appears to improve under noise stress. One of these situations is the rod and frame test, in which a subject in a darkened room is to adjust a faintly luminous rod to the vertical. The rod is enclosed within a tilted luminous frame which suggests a false orientation. To determine the true vertical, the subject must ignore this visual cue and rely on kinesthetic sensations. Performance in this task improves in the presence of loud background noise (Oltman, 1964).

Another task in which performance improves in noise is the Stroop test, which will be discussed in more detail in Chapter 6. In the most difficult condition of this test, subjects are shown a card in which names of colors are printed in inks of different colors. They are required to report the color of the ink in which each word is printed, suppressing the tendency to read the word itself. Performance in this condition improves in loud noise (Agnew & Agnew, 1963; Callaway & Stone, 1960; Houston, 1969; Houston & Jones, 1967). What improves in noise is specifically the ability to control interference. Thus, there is no interference when subjects merely name the colors of neutral symbols, and performance in this easier condition is actually worse in noise than in quiet (Houston, 1969; Houston & Jones, 1967).

Although these results appear to support Easterbrook's hypothesis that high arousal enhances selectivity, Houston and Jones (1967) found reasons to doubt this interpretation. Noting that drug stimulants and noise do not produce identical effects on the Stroop test (Callaway & Stone, 1960; Quarton & Talland, 1962), they suggested that it is the struggle to inhibit irrelevant responses to the noise which enhances the subject's ability to inhibit the irrelevant Stroop responses. This attractive hypothesis is consistent with physiological evidence of an inhibitory set in the Stroop test (see p. 32). The same hypothesis would also explain the improvement of performance on the rod and frame test under noise. The methodological implication is clear: a change of behavior can be explained as a consequence of arousal only if it occurs in several conditions of high arousal, e.g., both in noise and after the ingestion of stimulant drugs. These converging operations have not been used in all the situations to which Easterbrook's hypothesis has been applied.

This note of caution notwithstanding, the weight of the evidence does favor the conclusion that high arousal restricts the range of cues among which attention may be divided, and also disrupts the control of selective attention. In the terms of a capacity model, the allocation of capacity becomes both more uneven and less precise when arousal is high. Consequently, performance is impaired in tasks that require either the deployment of attention over a broad range of information-processing activities, or the control of selection by fine discriminations.

Easterbrook (1959) has attempted to account for all the effects subsumed under the Yerkes-Dodson law by the single hypothesis that cue utilization is narrowed by increasing arousal. However, this theory appears inadequate on several grounds. First, it implies the unlikely idea that the difficulties of the under-aroused, drowsy subject result from an excessive openness to experience. Second, it suggests that concentration is highest when arousal is high. This is contrary to everyday observation, which indicates that a state of high arousal is associated with high distractibility.

The apparent paradox that rigidity and lability of attention both rise with arousal has often been noted (Callaway & Stone, 1960). To resolve this paradox a distinction must be drawn between the breadth of allocation of attention at any one time and the stability of allocation over time. Wachtel (1967) emphasized this distinction. He quoted Hernandez-Peon's (1964) description of attention as a "beam of light in which the central brilliant part represents the focus, surrounded by a less intense fringe," and noted that such a beam has two characteristics that could define breadth of attention: its width, and the extent to which it roams in scanning the field of stimulation. These two characteristics are conceptually independent, and a proper definition of breadth of attention must explicitly separate the width of the beam from its stability. Wachtel defines beam-width in terms of the number and range of cues that are integrated in a judgment or percept. One example of narrow beam-width is the consistent failure of children in tests of conservation of number or quantity, which Piaget has attributed to excessive concentration on one salient attribute at a time.

The evidence presented earlier regarding Easterbrook's hypothesis is consistent with the idea that high arousal narrows the attentional beam. The evidence concerning the effects of arousal on scanning is far less conclusive, but clinical observation suggests that extremely high arousal may lead to an increase in scanning, with a corresponding increase in distractibility (Korchin, 1964) and a consequent disorganization of behavior. It is perhaps relevant that a very high saccadic rate is observed after the ingestion of LSD-25 (Kohn & Bryden, 1965). If it is true that the allocation of attention becomes both narrower and more labile under high arousal, the disruption of complex performance is inevitable.

Variations of arousal have other effects on performance. For example, Broadbent (1971) has discussed the effects of arousal in a prolonged vigilance task, where subjects are to detect occasional signals and report their confidence in each detection. Under the effect of noise, fewer responses are made at an intermediate level of confidence: subjects tend to be either very sure or very unsure of their detections.

Arousal also affects the speed-accuracy tradeoff, i.e., the balance which subjects spontaneously adopt between speed and the avoidance of errors. In reviewing the literature on effects of noise, Broadbent (1957b) noticed several studies which suggested that work tends to be faster but less accurate under noise.

Posner, Klein, Summers, and Buggie (1973) have reported a detailed analysis of speed-accuracy tradeoff in choice reaction-time as a function of the duration of the foreperiod. It is well known that RT is reduced if the stimulus is preceded by a warning signal, but the facilitating effect of the warning signal requires a foreperiod of 0.5 seconds to develop fully. Posner and Boies (1971) had interpreted this effect as a preparatory rise in alertness. Subsequently, Posner, Klein, Summers, and Buggie (1973) showed that the effect of the foreperiod in reducing RT is sometimes associated with an increase in the number of errors. Apparently, the surge of arousal which is caused by the warning signal does not simply improve the overall effectiveness with which the task is performed, but it alters some aspects of the subject's strategy in dealing with the task.

Some aspects of learning also show systematic changes with arousal. Several investigators have reported that items which elicit a large galvanic skin response (GSR) at presentation are retained better than other items after a long retention interval, but worse than other items if the retention test is immediate (Kleinsmith & Kaplan, 1963, 1964; Walker & Tarte, 1963; Corteen, 1969). Similar results have been obtained by presenting bursts of noise during the learning period: immediate recall was often impaired, but forgetting was slower (Berlyne, Borsa, Craw, Gelman

& Mandell, 1965; Berlyne, Borsa, Hamacher & Koenig, 1966; Berlyne & Carey, 1968). Thus, short-term memory appears to be impaired by high arousal (Easterbrook, 1959), while long-term memory improves. Further evidence for the dependence of short-term memory on arousal was obtained in studies of the diurnal rhythm. Physiological arousal level is known to increase gradually during the day (Kleitman, 1963), and performance in most tasks shows a corresponding improvement. Immediate memory, however, shows a significant decrease between morning and afternoon (Baddeley, Hatter, Scott & Snashall, 1970; Blake, 1967). The interpretation of these results has usually been in terms of a direct effect of arousal level on the consolidation of memory traces. An alternative hypothesis is that subjects engage in more active rehearsal when highly aroused, and that the effects of such rehearsal are beneficial for long-term retention and detrimental for short-term recall.

In summary, the evidence reviewed in these sections suggests that a state of high arousal is associated with the following effects: (1) narrowing of attention; (2) increased lability of attention; (3) difficulties in controlling attention by fine discriminations; and (4) systematic changes of strategy in various tasks. On the other hand, a state of extremely low arousal may cause: (1) a failure to adopt a task set; (2) a failure in the evaluation of one's performance, resulting in an insufficient adjustment of the investment of capacity to the demands of the task (see Fig. 3-3).

The Orientation Reaction

The model of attention which has been developed in these chapters assumes that the allocation of capacity is determined principally by two sets of factors: the momentary task intentions of voluntary attention and the more enduring dispositions which control involuntary attention. These enduring dispositions cause us to pay more attention to some stimuli than to others. Novel stimuli, in particular, are favored in the allocation of capacity.

The pattern of physiological responses which is elicited by novel stimuli is variously named the orientation reaction, response, or reflex (OR). It was first discovered and described by Russian physiologists (Pavlov, 1927; Sokolov, 1963, 1965), and the experimental results available up to 1965 originated almost entirely in Russian laboratories (Lynn, 1966). Subsequent studies in the West have usually confirmed the conclusions of the Russian investigators.

The OR and states of high arousal, such as pain or fear, share several components: EEG desynchronization (alpha blocking) and manifestations of sympathetic dominance, including the galvanic skin response

(GSR) and the dilation of the pupil. However, Sokolov has distinguished the orientation reaction to novel stimuli from the defensive reaction to aversive and painful stimuli. The arousal pattern is commonly identified with the defensive reaction. The most important difference between orientation and defense is that the OR is characterized by vasoconstriction in the limbs and vasodilation in the head, while the defensive reaction includes generalized vasoconstriction. Sokolov considered this dissociation of the vascular response so important that he tended to use it as an operational definition of the occurrence of an orientation reaction. This usage has not generally been adopted in the West, where several experimenters have confirmed that peripheral vasoconstriction follows novel stimuli (e.g., Unger, 1964; Zimny & Miller, 1966), while others have failed (Cohen & Johnson, 1971; Keefe & Johnson, 1970; Raskin, Kotses & Bever, 1969a, b). Western investigators tend to use the GSR (e.g., Germana, 1968; Maltzman & Raskin, 1965) or a transient desynchronization of the EEG (Berlyne & Borsa, 1968) as measures of the OR. Unfortunately, these measures do not distinguish the specific OR pattern from related states, such as emotional arousal and mental effort.

The OR precedes and dominates other responses to the same stimulus (Sokolov, 1963; Zimny & Kienstra, 1967; Zimny & Miller, 1966). This is shown most dramatically by the reaction to sudden immersion of the hand in hot water. Although the adaptive reaction to this stimulus is a peripheral vasodilation which facilitates heat loss, the initial response to immersion in hot water is a typical OR, complete with peripheral vasoconstriction. Only after a few seconds does the adaptive response predominate. The OR similarly dominates early responses to aversive stimuli, such as electric shock, which later elicit the defensive pattern of vasoconstriction in both head and limbs. After a few repetitions the OR diminishes in both extent and duration, until it eventually vanishes completely and only those adaptive or defensive reactions remain that are appropriate to the stimulus.

Habituation with repetition is the most important characteristic of the OR. For example, when a subject is instructed to "listen to tones," the first and perhaps the second tones elicit very substantial GSR's, but a low steady state is reached with a few presentations (Uno & Grings, 1965). The habituation of the OR does not imply that the stimulus is no longer registered or analyzed. Rather, the subject has learned to expect the stimulus, and the OR is only released when the characteristics of the stimulus violate expectations. Sokolov (1969) has provided a compelling demonstration of this expectation effect: when a single flash of light is omitted from a regular series, a major OR occurs soon after the time at which the omitted light was due. Similar results have been described by Badia and Defran (1970), among others.

Sokolov has presented a "neuronal model theory" to account for such results. According to his theory, an incoming sensory message reaches analyzers at the cortex which match its features to neuronal models constructed by previous experience. A mismatch between stimulus and model triggers an orientation reaction, which is controlled by subcortical centers. An interesting feature of this theory is the idea that stimuli are analyzed at the cortical level *before* the decision is made to activate the system by an OR: the cortex appears to be the only structure capable of performing the precise analyses that determine if a stimulus is familiar or novel. However, the elicitation of the OR also influences the subsequent activity of the cortex itself. The processing of a novel stimulus is therefore recursive: the output of a preliminary analysis at the cortex is eventually fed back to control subsequent cortical activity.

Figure 3-4 explains in terms of a recursive process the detailed and intense study of a novel stimulus which is one of the salient manifestations of the OR. The figure illustrates the two types of input, information and effort, which affect perceptual processing in a capacity model. In this example, the information from preliminary analyses of a novel stimulus causes the allocation of greater effort to elaborate the analysis of that stimulus. Although several stages are indicated, the entire cycle can probably be completed within 150–200 milliseconds. Chapter 4 will show that the decision to fixate on a particular area in visual search involves similar considerations, and such decisions are made several times every second.

Sokolov's concept of neuronal models raises interesting problems: what are the characteristics of such models, and how are they constructed? In general, of course, the neuronal model is set by repetition of the same stimulus, but it has been shown that repetition is not essential. A definite expectation, whatever its source, sets up a neuronal

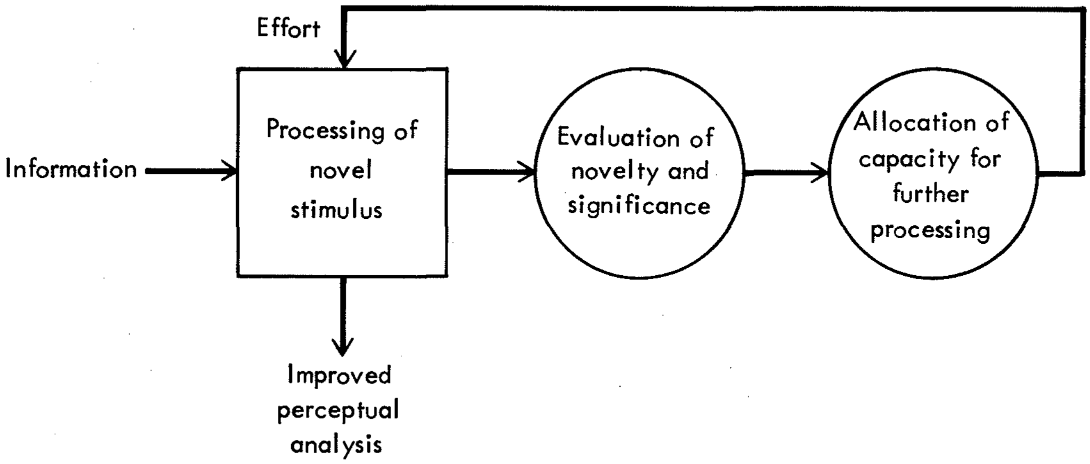

FIGURE 3-4
Recursiveness in the processing of a novel stimulus.

model, and the violation of an expectation elicits an OR. Thus, Unger (1964) presented a series of numbers in ascending order, and he found an orderly disappearance of the OR to successive numbers, and an obvious OR to a number presented out of sequence (e.g., 11, 12, 13, 17). Similar results have been reported by Maltzman and Raskin (1965), and less conclusively by Zimny, Pawlick, and Saur (1969).

In some situations, however, the neuronal model and the subject's conscious expectancies probably do not coincide. Thus, Maltzman, Harris, Ingram, and Wolff (1971) exposed subjects to a constant level of illumination for ten minutes. The illumination was then changed, then restored, in a series of regular alternations. Although the subjects surely realized the repetitive pattern of events, they continued to show larger OR's when the illumination was changed from the initial adapting level than when it was restored to that level. The initial adaptation period had apparently established a neuronal model which defined some changes of illumination as deviations from the standard, and others as restorations of standard conditions.

Furedy and Scull (1971) exposed subjects to a random sequence of two possible events. They noted that repetition of the same event caused a smaller OR than alternation. This result is particularly interesting because the verbal expectations of subjects in such situations usually show a negative recency effect, favoring alternation over repetition. The neuronal model apparently represents a more primitive type of "expectation" than is normally verbalized. In a very different context, Epstein and Rock (1960) had also observed a marked positive recency effect which overshadowed cognitive expectancies. In a series of trials, they alternated presentation of two profiles. On a test trial, two profiles were combined into an ambiguous figure, and the subjects were asked what they "saw." There was a marked tendency to see the profile that had been shown on the preceding trial rather than the profile that was consciously "expected."

Neuronal model theory describes a system which monitors the fit of events to some type of expectation and triggers an OR whenever the fit is poor. In this view the neuronal model is an automatic novelty detector, and novelty is a sufficient condition for an OR. This is not, however, strictly true: novelty is only one important contributing factor to the elicitation of an OR, but it is neither a sufficient nor a strictly necessary condition.

The significance of the stimulus to the organism is a second major determinant of the OR. Razran (1961, p. 118) describes an experiment by Biryukov in which fox cubs were exposed to the squeaks of mice. The OR's to these squeaks soon extinguished. If the cubs were allowed to eat the mice, however, a single meal sufficed to make the OR essentially permanent. The continued effectiveness of a signal stimulus, one's own name, for example, also demonstrates the role of significance. Such a stimulus, although hardly novel, is a potent elicitor of the OR.

Bernstein (1969) has stressed the marked dependence of the OR on stimulus intensity as another indication that novelty cannot be the sole determinant of the OR. He suggested a two-stage model in which the novelty and the potential significance of a stimulus are both evaluated before an OR is released. Bernstein *et al.* (1971) further supported this view by showing that apparent motion of a pattern toward the subject (looming) elicits a larger OR than apparent motion into the distance.

Pavlov (1927) viewed the autonomic changes of the OR as part of a more general pattern, which he called the "what is it?" reflex. This pattern includes various adjustments which facilitate sensory registration, notably a marked increase in the rate of eye movements. However, the functional significance of other manifestations of the OR has not been established.

Sokolov (1963) emphasized the idea that a major function of the OR is to improve sensory receptivity, and he claimed that thresholds are lowered during the OR, both by peripheral adjustments, such as pupil dilation, and by central sensitivity changes. Although plausible, this idea should not be accepted uncritically. The argument that a large pupil enhances sensitivity is doubtful, for example, because gains in sensitivity to light are probably offset by a loss in the quality of the retinal image. The observation that weak or ambiguous stimuli elicit a large OR (Sokolov, 1963, 1965) may well represent the subject's effort to process these stimuli rather than any enhancement of peripheral sensitivity. When subjects are instructed to make discriminations about stimuli, large pupillary responses occur on the presentation of weak (Hakerem & Sutton, 1966) or ambiguous stimuli (Kahneman & Beatty, 1967), because the analysis of such stimuli demands much effort. Similar responses probably occur when the organism spontaneously engages in detailed processing of an alerting stimulus. In this interpretation, a weak stimulus does not directly elicit a large autonomic response. It elicits a surge of effort, which is accompanied by autonomic manifestations of arousal.

It has sometimes been suggested that the facilitation of learning is one of the functions of the OR. Indeed, the first phase of classical conditioning is normally the development of a marked OR to the conditioned stimulus. Conversely, when repeated presentation has thoroughly habituated the OR to a stimulus, that stimulus becomes ineffective, and it is very difficult to attach any response to it (Sokolov, 1963, p. 244). When one no longer pays attention to the occurrence of an event, it is difficult to learn anything new about it.

The OR cannot be likened to a stereotyped reflex because the correlations among its various manifestations are not very high. It is better viewed as a set of independently controlled changes, which usually occur together because they are often adaptive on the same occasions. Figure 3-5 presents such a view of the OR.

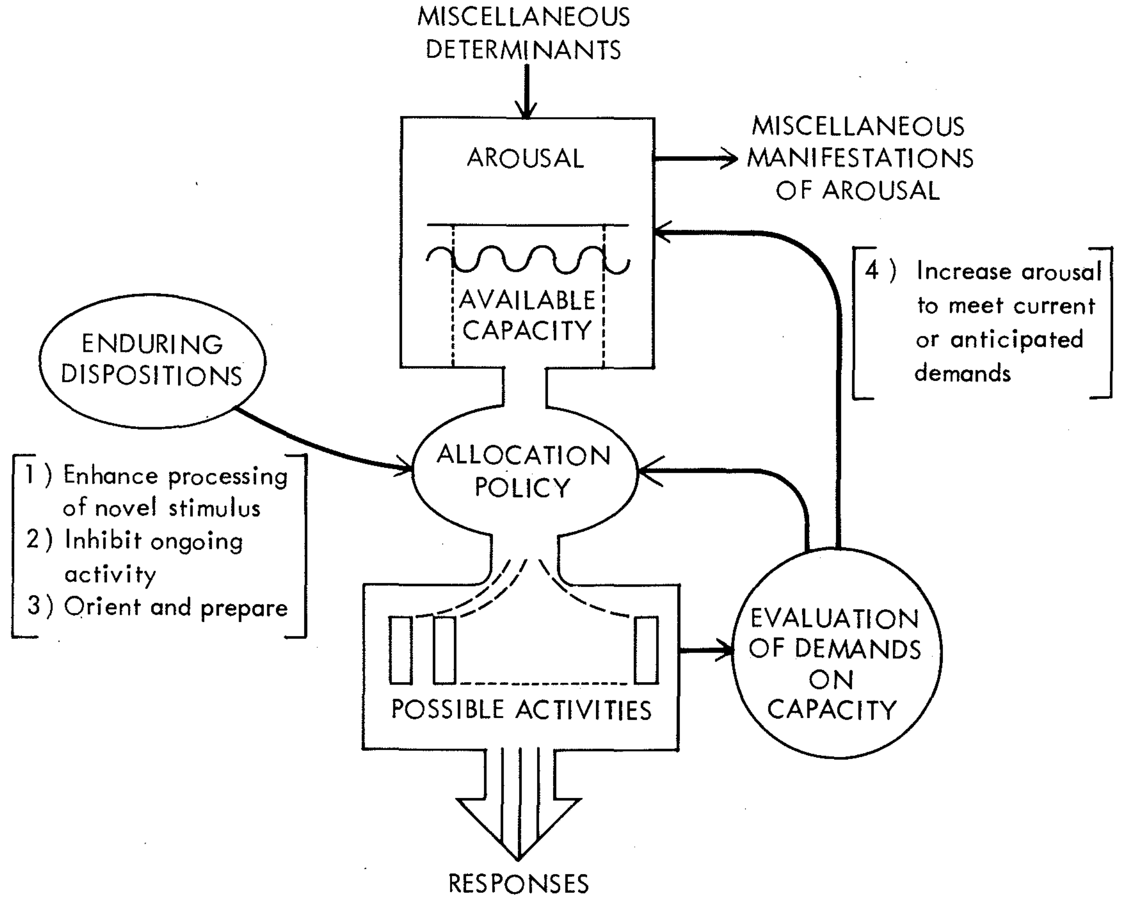

FIGURE 3-5
Components of the orientation reaction.

The figure distinguishes four components of the OR.

(1) A transient effort to process and analyze the alerting stimulus. The effort component of the OR will be most significant when the alerting stimulus is novel, complex, or barely discernible. The effort required to process a stimulus is probably much greater on the first presentation of a stimulus than on subsequent occurrences: with the construction of a neuronal model, processing effort habituates. Conversely, if rapid habituation of the OR is observed, as in the repeated presentation of a tone, we can infer that effort was a dominant element in the original OR's.

The present analysis of effort in the OR applies to cases in which the allocation of attention to the stimulus is involuntary, governed by enduring dispositions. It seems important to distinguish these cases from others, in which the subject is instructed to make decisions and execute specific responses to stimuli. Autonomic responses in these situations of voluntary effort should not be identified as OR's. Much confusion has been caused by inconsistent usage in this context.

(2) *Inhibition of ongoing activity.* This is a very salient feature of the response to novel stimuli in normal situations. The inhibitory aspect of the OR is often obscured in the laboratory situation, which is typically rigged to prevent or minimize spontaneous activity at the time of stimulus presentation. The presence of a pronounced deceleration component in the cardiac OR, which consists of a succession of accelerations and decelerations (Chase, Graham & Graham 1968; Connor & Lang, 1969; Graham & Clifton, 1966), probably reflects this inhibitory aspect. The inhibition of irrelevant activity facilitates a rapid and effective response to the novel stimulus and to other significant stimuli that may follow it.

(3) *An orientation toward probable sources of future significant information.* The increase in ocular motion, and the pricking of the ears in cats and dogs are components of the OR, which are obviously related to an enhanced readiness for relevant stimulation. These adjustments are not random or diffuse. An alerting sound from a particular direction reliably elicits postural changes to facilitate the registration of additional stimuli from the same direction. There is also an immediate increase in the readiness to respond in the direction of an eliciting stimulus. Simon (1969; Craft & Simon, 1970; Simon, Craft & Small, 1970) has studied the effects of sounds delivered from various directions on the performance of speeded directional responses. This work demonstrated "a potent natural tendency to react toward the major source of stimulation [Simon, Craft & Small, 1970, p. 63]." Unfortunately, experimental arrangements often minimize the postural aspect of the OR: stimuli are typically presented in the frontal plane, or through headphones. However, any comprehensive description of the response to unexpected stimuli must emphasize the postural adjustments that serve orientation.

(4) *A transient increase of arousal.* It has been emphasized that the cardiac and vascular components of the OR differentiate it from other cases of heightened arousal. These specific aspects of the OR are probably related to its inhibitory and preparatory functions, but the OR also represents an increase in arousal level. This increase of arousal does not appear to be controlled by feedback from ongoing activity. Rather, it seems that when the system can anticipate a particular activity, it allocates capacity to that activity in advance of relevant stimulation. An anticipatory mobilization of capacity may well occur in other situations, such as the foreperiod in a reaction-time task. However, the evidence

of the foreperiod effect suggests that the anticipatory surge of arousal cannot be effectively sustained over a long period.

In summary, the OR should be viewed as a loosely organized set of physiological changes, each independently controlled by some aspect of the stimulus situation and of the response to that situation. The OR consists of an effort to analyze the alerting stimulus, and of a complex pattern of preparation for future stimuli and responses.

REVIEW

The chapter was concerned with several connections between arousal and attention.

The first section showed that the nature of the task situation determines the pattern of autonomic responses. At least two states of intermediate or high arousal must be distinguished. The standard arousal pattern is associated with active processing and with the performance of motor responses. An inhibitory pattern is adopted in passive acceptance of stimuli, in states of waiting, and in states of response conflict. This pattern is characterized by directional fractionation: the heart slows down even as other indices suggest an increase of arousal level.

The Yerkes-Dodson law states that performance is an inverse U-shaped function of arousal level. The failures of under-aroused subjects were interpreted in motivational terms. The failures of over-aroused subjects were interpreted in terms of Easterbrook's hypothesis: in high arousal, attention tends to be concentrated on the dominant and most obvious aspects of the situation. In addition, high arousal impairs the ability to discriminate relevant from irrelevant aspects, and increases the lability of the allocation policy. These changes cause a decrement of performance in high arousal, which is most obvious in tasks that require a wide range of cues or fine discriminations.

An enduring disposition causes a specific allocation policy to be adopted when novel and significant stimuli are detected. Some aspects of this policy are manifest in the orientation response (OR), which consists of an inhibition of ongoing activity, intense processing of the novel stimulus, and various preparations for future stimuli and responses.

4

Looking

The allocation of attention has both instantaneous and sequential aspects. At any point in time, attention can be divided among several activities. In addition, the focus of attention changes from instant to instant, in an organized fashion. The act of looking provides a basic example of this sequential organization of selective attention. The world extends 360 degrees around us, our field of vision spans about 210 degrees, but vision is sharp only within a small foveal region of about 2 degrees, and the rate at which this narrow beam of sharp vision can be moved is limited to about 3–5/second. The question of where to direct this beam is obviously of great adaptive significance, and the mechanisms that have evolved for the control of eye position and eye movements are of exquisite precision.

A description of the physiology of oculomotor control is beyond the scope of this book (the interested reader should consult a review by Alpern, 1971). It is sufficient to note that two distinct mechanisms control two major types of eye movements. Most eye movements are saccades, very rapid movements which are planned in advance and are executed without continuous control during the movement itself. This so-called ballistic character of the saccade permits it to be executed at high speed. The other type of eye movement is pursuit, a smooth motion which occurs only when the eye fixates a moving object. Smooth motions of the eye do not occur in the absence of a moving object in the field, and the eye cannot be moved slowly from one locus to another, except in pursuit.

Looking is obviously under voluntary control, because one can decide where to fixate, but conscious and deliberate control of fixation is actually infrequent. As with other highly skilled components of voluntary performance, such as walking or the maintenance of balance, looking is controlled by a general intention, and consciousness plays a minor role in the execution of the intended sequence of fixations. The processes that determine the locus of individual fixations are psychologically silent, and their feedback is so poor that people do not usually know precisely where they are looking.

The precise measurement of eye movements and eye position by photography or electrophysiological measures is a laborious procedure which requires sophisticated equipment. However, because people are unaware of the precise locus of their fixation at any time, a simple alternative technique can be used to provide crude estimates of fixation tendencies. Kaufman and Richards (1969) have recently reintroduced this technique, which was known in the nineteenth century. The equipment consists of a slide or movie projector, fitted with a blue filter and with a polarizing filter which can be made to rotate at slow speed. A non-depolarizing projection screen is also required. The observer sees whatever image is projected on the screen. In addition, he sees a small fuzzy line whirling on the screen whenever the polarizing filter rotates. The line is actually the shadow cast on the observer's fovea by crystalline structures in his eye (called the Haidinger brush). This shadow is normally invisible because it is stabilized on the retina, but the rotation of the polarizing filter causes the shadow to disappear and reappear intermittently, and this makes it visible to the observer. Naive observers, however, are invariably convinced that the whirling shape on the screen has been projected by the experimenter, and they can be asked occasionally to indicate the position of the shadow on a map, thus providing a record of where they are looking at the time. Kaufman and Richards (1969) have documented the fact that subjects are often ignorant of the true locus of their fixation. Moreover, they can be exposed to the Haidinger brush repeatedly before discovering its relationship to their eye.

Looking behavior is never random. When one's activities require the intake of visual information, the movements of the eye adjust to that function. In the absence of a specific task set, the control of fixation is handled by enduring dispositions and standard routines of "spontaneous looking." These routines, many of which are probably innate, tend to select stimuli that are ecologically likely to be significant. The enduring dispositions that control spontaneous looking include all the dispositions that call for spontaneous attention in the orientation reaction, as well as additional factors which affect looking without affecting autonomic activity. Finally, looking is closely involved in cognitive activities that have little or nothing to do with visual intake: highly consistent patterns of eye movements accompany various types of mental activity, and various tasks of selective attention with auditory stimuli.

The determinants and manifestations of spontaneous visual attention are discussed in the next section. Subsequent sections deal with the deliberate intake of visual information, and with situations in which the content and direction of mental activity are the main determinants of looking behavior.

Spontaneous Looking

In the absence of a specific instruction to search for visual information, spontaneous looking is controlled by enduring dispositions that determine which parts of the field of view should attract and hold the gaze. Berlyne (1960, 1966) has distinguished two classes of stimuli that attract spontaneous attention: physical properties, such as the presence of many contours, and collative properties, such as novelty, complexity, or significance.

The distinction between physical and collative properties is not sharp, however, because collative properties, in their most elementary form, can be reduced to physical properties. Novelty and complexity are important collative properties that control spontaneous attention in the adult. The infant is already very responsive to the most elementary level of complexity—an isolated figure in a blank field—and to the most elementary level of novelty—movement (Gesell & Ilg, 1949). Human infants who are given a choice of two patterns in their visual field (Fantz, 1958) show an immediate preference for relatively complex stimuli: patterned stimuli are preferred to homogeneous gray patches (Fantz, 1965a; Hershenson, Munsinger & Kessen, 1965), and within the first few months there is a gradual development of preferences for complex random arrays over simpler displays (Fantz, 1967), for radial over linear patterns, and for solid over two-dimensional figures (Fantz, 1965b).

Some of the collative factors that attract the spontaneous attention of human adults have similar effects on the behavior of lower animals. The effect of novelty on viewing time, for example, is not restricted to humans: Berkson (1965) has shown a very rapid decrease of viewing time with repeated exposures in infant chimpanzees. Complexity also controls attention similarly in humans and monkeys: Brown and Gregory (1968) found that the number of sides in a visual pattern (a measure of complexity) affects the visual attention of adult humans and determines how easily a visual discrimination can be learned by squirrel monkeys.

Novelty and incongruity are defined by a mismatch between stimulation and a neuronal model of expectations. For example, Berlyne (1957, 1958; Berlyne & McDonnell, 1965) showed that the attention of adult subjects is attracted by incongruous pictures such as a camel with a lion's head. The neuronal models of the adult, of course, are vastly more elaborate than those of the infant, who would surely not respond to such manipulations of incongruity. However, the rule that novel and complex stimuli attract spontaneous attention is valid at all stages of development. Moreover, the adult's ability to develop highly sophisticated patterns of expectations merely supplements the innate rules of spontaneous attention without replacing them. Adults retain an extremely powerful tendency to direct their gaze toward moving objects and to scan contours, and they tend to fixate an isolated object in the field even when it carries no information.

Adult subjects also respond very consistently to trivial manipulations of visual complexity such as the number of sides of a shape or the variability of their length (Brown & Gregory, 1968). An important observation here is that the function which relates spontaneous attention to complexity has the shape of an inverted U. Excessively complex stimuli are treated as irrelevant noise and no longer attract attention.

Spontaneous attention can be measured in several ways, and the same stimulus properties invariably dominate results. Novel, complex, and incongruous objects are always fixated in preference to others (e.g., Berlyne, 1958; Day, 1965), and subjects also spend more time looking at such stimuli when given control of a device which presents pictures successively (Berlyne, 1957; Berlyne & Lawrence, 1964). The same collative properties also determine which of several concurrent stimuli will control behavior in a situation of conflict. Berlyne has introduced an experimental paradigm to study this type of stimulus choice (Berlyne, 1950, 1951, 1967, 1970; Berlyne & Lawrence, 1964; McDonnell, 1967, 1970): the subject fixates a mark located at an equal distance from several windows. Under each window there is a response button, which the subject presses whenever a picture appears. When several pictures are shown simultaneously, the subject is to press only one of the buttons, and the aim, of course, is to discover which he will push. A plausible assumption is that one presses the button corresponding to the most attractive or compelling stimulus. Results show that the same collative and physical variables that determine the choice of fixation and the duration of free viewing time also control immediate and undeliberate choice in a conflict situation (Berlyne, 1966). The next chapter will show that related factors also determine which area in the visual field spontaneously emerges as figure over the background (see Fig. 5-3 on p. 77).

A stimulus which is novel, complex, or incongruous certainly demands greater processing effort than a stimulus distinguished by none of these properties. Thus, a basic rule of the allocation policy appears to be that perceptual activities which demand much capacity are favored over less demanding activities. This rule already controls the looking behavior of infants, and it remains valid in adults.

Although pleasure-seeking is often seen as a basic principle of behavior, spontaneous looking does not seem to conform to this principle. The best evidence has been obtained in the free-viewing paradigm, in which subjects are given control of the time they spend viewing a series of abstract pictures. The behavior of subjects who are given no specific instructions tends to be similar to the behavior of subjects instructed to linger on "interesting" stimuli, and quite different from that of subjects who follow a "pleasingness" set. Three-sided shapes, for instance, are judged more pleasant than nine-sided shapes, but they are looked at less, in the absence of special instructions (Brown & Farha, 1966). Berlyne and Lawrence (1964) and Day (1966) also found a negative correlation between free viewing time and verbal preference for irregularity of shape. Observations of this kind suggest that the enduring dispositions which control spontaneous attention reflect epistemic motivation, the need to perceive clearly and to reduce uncertainty (Berlyne, 1960, 1965; Durham, Nunnally & Lemond, 1971; Nunnally, Faw & Bashford, 1969; Woodworth, 1958).

It must be mentioned, however, that spontaneous looking is not always controlled by epistemic motivation. The widespread use of female beauty in advertising does not appeal to collative variables. More generally, the needs and values of individuals determine what they find interesting, and what they prefer to look at. Extroverts, for example, prefer to look at a picture of a party than at a picture of a lone man reading a book (Bakan & Leckart, 1966). And a subject whose Rorschach responses classify as a "repressor" may studiously avoid a bare-breasted woman in a picture, concentrating instead on a man reading a newspaper (Luborsky, Blinder & Schimek, 1965).

Yarbus (1967) has studied patterns of fixations during prolonged observation of pictures. Figure 4-1 presents two of his pictures and typical records of fixation sequences. A striking feature of these records is their repetitive nature: in the left panel, fixations repeatedly travel back and forth between the girl's eyes, and in the right panel they repeatedly climb the trees. The right panel also illustrates the roles of both physical and collative properties in the control of spontaneous looking: the selec-

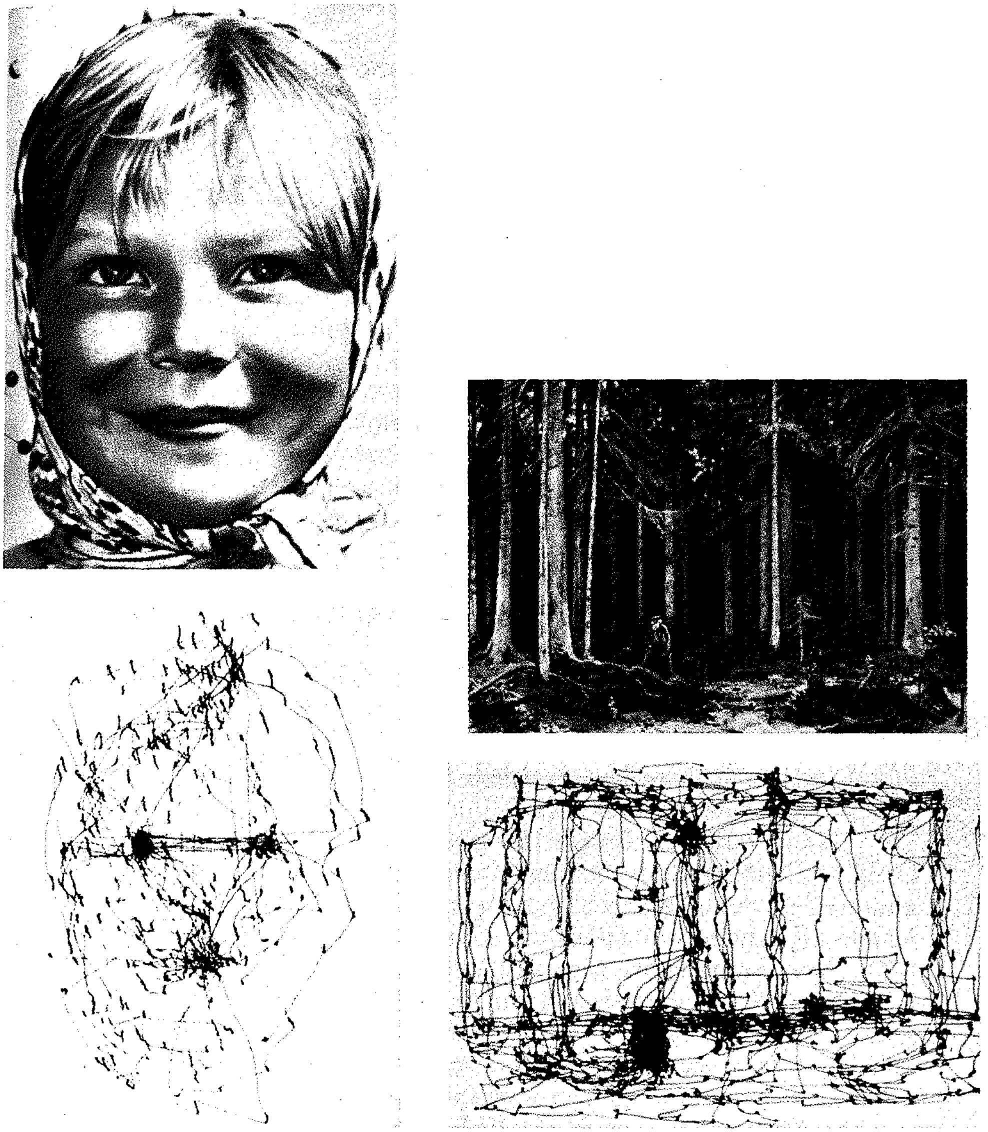

FIGURE 4-1
Records of eye movements during the continuous observation of two pictures (from *Eye Movements & Vision* by A. L. Yarbus, with permission).

tion of the trees that are often fixated is controlled by the physical property of brightness contrast, but the large numbers of fixations on the human figure must be attributed to collative factors.

THE ACQUISITION OF VISUAL INFORMATION

Looking at simple figures is governed by simple rules, of which several are innate. The rules of fixation guide the eye to areas which are ecologically likely to be most informative. Thus, Salapatek and Kessen (1966) have shown that infants typically follow contours in scanning a triangle; contours, of course, define the shape of objects. Brightness contrast is also significant, and for sound ecological reasons: a sharp contrast between adjacent areas of the two-dimensional scene is likely to represent a demarcation between two objects which are located at different distances from the observer. These rules govern infants' fixations and are retained in the adult. For example, Kaufman and Richards (1969) found that the fixations of adults hover near a vertical contour separating a field into a dark and a lighter area, with a bias in favor of the lighter area. With figures that span more than 5 degrees, the eye tends to stay near the center of the figure.

The innate routines which control the infant's fixations are the precursors of the more complex operations which direct the eye of an older person to the most informative areas of a scene. In scanning a picture of a family scene, for example, a sophisticated observer will look at the furniture to answer a question about the family's financial circumstances and he will look at the children when attempting to guess how long the parents have been married. This type of information search has been documented by Yarbus (1967).

Mackworth and Bruner (1970) studied the eye movements of both children and adults who were attempting to recognize an object in a blurred picture. The area of the picture was divided into 64 squares, and each square was rated for informativeness by independent judges. The most informative areas attracted more fixations (Mackworth & Bruner, 1970; Mackworth & Morandi, 1967), although the correlation was far from perfect. Mackworth and Morandi (1967) reported the important finding that informative areas are identified very early in the observation of pictures; the average informativeness of fixated areas is already high in the first two seconds of observation. Similar conclusions have been reported in other studies of eye movements (De Groot, 1966; Jongman, 1968; Yarbus, 1967).

Although an adult can very quickly decide where to look next, this decision often depends on a highly sophisticated weighting of many factors. Thus, the control of the eye is one of man's most accomplished skills.

A fixation is often determined on the basis of information previously acquired in peripheral vision. Williams (1966) studied this process in an elegant experiment: his subjects were shown a large array of figures, each including a number. The figures varied in color, size, or shape. On each trial the subject was told to look for a particular number, and he was given some information about the figure containing the target number, e.g., its color or size. Subjects found it easy to restrict their fixations to figures of the designated color, thus reducing search time. They could also use the size cue to some extent, but they were essentially unable to control search by shape cues.

An instructive example of the skilled control of eye movements was reported by Gould and Schaffer (1965). Their subjects were shown an array of digits and were required to count the occurrences of a particular target digit. Subjects most easily detected the digit 7 and found 9 and 2 the most difficult. They did not always fixate on targets that they recognized, but their fixations tended to come closer to the difficult 2's and 9's than to the easier 7's. In addition, the difficult targets were more often fixated directly. Evidently, subjects often decided to have a closer look at the more difficult targets. An impressive aspect of decisions like these is their speed: the decision must depend on an evaluation of the information acquired during the current fixation, yet the whole cycle is normally complete within 1/3 second.

Sanders (1963, 1970) studied the conditions under which a subject moves his eyes or head in order to obtain adequate information from a display. In some of his experiments the subject's task was to decide whether two simultaneously presented digits were identical. Sanders distinguished three ranges in the functional visual field: (1) *The stationary field,* in which the task can be carried out without scanning eye movements, i.e., when all relevant information is presented to central vision. (2) *The eye field,* in which the visual information acquired in a single glance only suffices to construct a hypothesis concerning the nature of the objects presented to peripheral vision. With a display that lies within the eye field, the subject has the two options of directing a fixation to the object originally seen in the periphery, or of acting on an unverified hypothesis. This decision to move the eyes or not is responsive to instructions, payoffs, and the nature of the display. (3) *The head field,* in which a head movement is usually needed to collect the necessary information. Again, the decisions appear to be made very rapidly and with little deliberation.

When a decision to redirect search must be made deliberately, it is slower and less effective. Neisser and Stoper (1965) trained subjects to perform a task of visual search over successive lines of printed material, with occasional marks indicating to the subject that he could safely skip a given number of lines. These marks were often ignored, apparently because the deliberate control of search required more time and effort than it could save.

A particularly interesting type of looking decision controls fixations in a monitoring task with multiple targets. Thus, an airline pilot faces more dials than he can see at a glance, and he must distribute his looking to maximize the probability that any significant event will be detected soon after it occurs. The probability that a dial contains new information is a function of at least two factors: the overall rate at which information is conveyed on that dial, and the elapsed time since the last look at it. Senders (1965) has used the mathematics of information theory to derive an optimal policy that determines the sequential allocation of looks among dials. He found that trained observers closely approximate optimal looking behavior. Evidently, the system which allocates looks is able to consider the changing probabilities that each of many dials will merit a look.

Senders (personal communication) has discussed the example of an adult reading a newspaper beside a swimming pool, while a baby is randomly crawling about in the area. At what intervals will the adult look up to check the baby's position? The interval will depend on where the baby was when last seen, and on its direction and rate of progress at the time. It will also depend on the depth of the pool, and on whether or not it is filled with water.

The duration of fixations appears to be less responsive to momentary fluctuations of attention than is their location. Although it is possible for an observer to maintain steady fixation for several seconds, the rate of fixations is normally much faster, and the fixations are usually rhythmic. Thus, a conclusion of the study of reading is that the difficulty of reading material has a greater effect on the number of fixations per line than on the duration of individual fixations, which averages 200-225 milliseconds (Morton, 1964; Tinker, 1947, 1958). In the observation of pictures, the common duration of fixation is 300-350 milliseconds (Mackworth & Bruner, 1970; Yarbus, 1967). Rhythmic motion occurs during uninstructed observation (see Figs. 4-1 and 4-2). Of course, ocular motion is necessary to prevent loss of vision from retinal stabilization (Riggs, Ratliff, Cornsweet & Cornsweet, 1953), but the spontaneous rate appears to be considerably faster than is necessary to avoid fading.

Under some conditions, however, the duration of an individual fixation may correspond to the attention that the object of fixation requires. An interesting pattern of results was reported in a series of studies by Gould. In the initial experiment, subjects scanned a display of numerals for occurrences of a target numeral (Gould & Schaffer, 1965). Although targets were fixated more often than non-targets, the duration of fixations on targets and on non-targets was the same. Different results were obtained in more complex tasks of pattern-matching (Gould, 1967; Gould & Dill, 1969; Gould & Peeples, 1970). Subjects in these studies were shown a nonsense pattern in the center of the display (the standard) surrounded by other nonsense patterns in the periphery. They were required to count as fast as possible the number of peripheral forms identical to the central standard. The initial study of the standard pattern was typically done in one prolonged fixation. During the search, fixations on target items were longer by about 80 milliseconds than fixations on non-targets. Furthermore, the duration of a fixation on a non-target pattern varied with the similarity between that pattern and the standard. In general, the same factors that determined the probability that a particular pattern would be fixated at all, also determined the duration of fixation on it, and the probability that it would be refixated. The difficulty of discriminating a pattern from the standard had a significant effect on all three measures. For fixation duration to reflect attentional demands, an extremely rapid decision process is required. Since fixations as short as 220-250 milliseconds were sometimes observed (typically on easily discriminable non-targets) it appears that the computation of whether a longer look was required must have been completed within about 150 milliseconds from the instant of fixation.

While prolonged fixations reflected visual attention in Gould's studies, they can also indicate inattention to the visual channel. Thus, Furst (1971) noted a progressive reduction of saccadic rate during the observation of a single picture, as well as an increasing stereotypy of fixation sequences and an increasingly steady rhythm. This pattern of habituation to a picture was reversed when the picture was repeated after an interval, indicating spontaneous recovery of visual attention.

A marked prolongation of fixations with continued exposure was found in subjects exposed to a Rorschach card (Thomas, 1963) and in radiologists studying an X-ray plate (Thomas & Lansdown, 1963). It is not altogether clear whether this effect was due to increased visual difficulties, or to inattention.

In general, the studies reviewed in this section indicate a fair correspondence between what the eye does and the demands of a set to search or recognize. There is direct evidence, however, that the linkage between fixation and attention is optional rather than obligatory. As Helmholtz already knew, one can look at one object and attend to another, and such attending can alter visual perception. Thus, Fraisse, Ehrlich, and Vurpillot (1956) demonstrated that the apparent size of objects to which one pays attention increases even when the attended objects are not fixated directly, and Grindley and Townsend (1968) have shown that deliberate attention to a peripheral area increases acuity in that area. The figure-ground effect, which will be discussed in the next chapter, is another illustration of an attentional effect that is not controlled by fixation, although we usually fixate the figure rather than the background.

It will be useful to summarize the information presented in this section and the preceding one, concerning the factors which control looking.

When fixation is governed by a visual task, the locus of fixation is determined by an assessment of the probabilities that relevant information will be acquired, and that the acquired information will be useful. Many factors can contribute to the assessment of these probabilities: known base rates for a particular area, and the elapsed time since the area was scanned (Senders, 1965); the detection of some features of a possible target, such as its color (Williams, 1966); a preliminary identification of a target (Gould, 1965; Sanders, 1963); and general knowledge about the structure of the situation (Yarbus, 1967).

When fixation is not controlled by a specific task set, it reverts to the control of enduring dispositions. Looking and attention are then spontaneous rather than deliberate. Two sets of enduring dispositions may be distinguished: innate routines which are triggered by specific physical features, and more elaborate responses which are mostly triggered by the mismatch between a stimulation and a neuronal model of expectations, i.e., by collative features.

The more elementary dispositions are usually overridden by a task set. However, a sudden change of the visual scene will usually elicit both an orientation reaction and a fixation toward the locus of change, even when one is engaged in a task. Thus, enduring dispositions and task set can override one another.

EYE MOVEMENTS AND THE SPATIAL ORIENTATION OF THOUGHT

Let the reader attempt to think of an object in the room, and he will soon become aware of a tendency to look at that object. When one person in a group conversation mentions the name of one of the people present, the collective gaze of the group is immediately drawn to the person mentioned. There seems to be a strong tendency to look where one thinks.

Eye movements of this kind represent a general orientation toward the object of thought. They occur even when the resulting visual stimulation is not useful. In experiments by Kahneman and Lass (1971), subjects were shown an array of four schematic line drawings of objects (automobile, person, tree, and airplane) and were asked questions such as "What makes of automobiles can you remember?" The Haidinger brush technique (Kaufman & Richards, 1969; see p. 51) was used to detect fixation tendencies. The eye quite regularly fixated the task-related object, although that object could provide no useful information. The hierarchy of the processes that control looking was clearly evident. When a single object was shown in the field, subjects almost invariably looked at it, regardless of whether it was relevant or not. When more than one object was shown, the relevant object was fixated. Finally, when the subject was questioned about a picture that was no longer present, he usually fixated that area of the blank screen where the relevant information had been shown.

Are these orientations helpful to performance of the task? In an attempt to find out, Kahneman and Lass compared subjects' performance when a relevant object was shown, when an irrelevant object was shown, and when the screen was blank. No significant effects were found. For example, subjects produced as many words with a specified letter in the third position when that letter was shown on the screen and when an irrelevant letter was projected. The irrelevant letter was fixated, but it did not interfere. In this study, at least, the preference for fixation on the relevant letter appeared to serve no purpose. In general, however, the correspondence of orientation to thought is adaptive, because it ensures that relevant information will be quickly acquired.

An impressive demonstration of the association between eye movements and internal processing was provided by Bryden (1961) and by Crovitz and Daves (1962), who showed that the locus of greatest accuracy in tachistoscopic recognition is related to the direction of eye movements following the stimulus exposure: for example, when the eye moves to the right, the far right figures are likely to be reported accurately. This is true although the eye movement occurs after the exposure and cannot affect sensory registration in any way.

A series of studies of eye movements during paired-associate learning provides further evidence of the correspondence between the locus of fixation and the focus of internal processing. The studies also provide a demonstration of the use of eye movements to test theories about internal events. A prevalent theory of paired-associate learning suggests that its first phase is response consolidation (Underwood, Runquist & Schultz, 1959; Underwood & Schultz, 1960). Correspondingly, during early phases of learning, the eye typically fixates the stimulus, then the response (S-R), and it lingers on the response item (McCormack & Haltrecht, 1966; McCormack, Haltrecht & Hannah, 1966, 1967). The tendency to fixate the response item is further enhanced when that item is low in meaningfulness (McCormack & Hannah, 1967; McCormack & Moore, 1969). The second stage of paired-associate learning has been identified as a phase of stimulus-response association. In that stage, the typical sequence of fixations is S-R-S, and the eye spends more time fixating the stimulus than the response. The patterns of fixation observed in these experiments certainly represent processing effort rather than information intake, because the exposure time (typically two seconds) is more than sufficient to acquire two visual nonsense syllables.

There has been much interest in the eye movements of chess players. De Groot (1966) and Jongman (1968) described the fixation patterns of master players, who were allowed to study a complex chess situation for five seconds in order to later reproduce it from memory. Many of the players immediately perceived the best possible moves for both opponents. Indeed, the master's eye quickly finds the area of main tension of the game, and the first fixation after the presentation of the display is already highly selective. Generally, however, the correspondence between the verbalizations of a chess player and his recorded looking behavior is far from perfect, and the master player often fails to fixate a piece about which he is much concerned. In the initial study of a position, possible sequences of moves are clearly perceived, but rarely mirrored by eye movements. When a player is allowed a longer period to study the board, the correspondence between fixations and the moves considered apparently improves after the first 10 or 15 seconds (Simon & Barenfeld, 1969; Tikhomirov & Poznyanskaya, 1966). In general, these investigations suggest that the movements of the "mind's eye" are correlated with those of the physical eye, but also that the correlation is optional rather than obligatory.

Another observation which demonstrates the optional nature of the correspondence between eye and thought was obtained by Kaplan and Schoenfeld (1966). They showed subjects five-letter anagram problems which could all be solved by the same transposition of the order of the five letters. Those subjects who discovered the rule usually announced their response after fixating each of the letters exactly once, in the order of their position in the solution. But other subjects were able to solve the anagrams without discovering the rule, and their sequence of fixations did not correspond to the solution.

Gopher (1971) studied the patterns of eye movements accompanying different tasks of auditory attention. The auditory messages were presented by earphones in his experiments, and eye movements could serve no function of sensory acquisition. Nevertheless, highly consistent patterns were observed. Eye movements were markedly inhibited when subjects listened to a monaural message (i.e., a message presented to a single ear), or when they were exposed to dichotic messages (i.e., different messages to the two ears) and were told to focus attention on one and ignore the other. When focusing attention, subjects almost always make a large saccade at the beginning of the message, invariably in the direction of the relevant ear and they maintain their fixation in that direction during the entire message. Dividing attention elicits a different pattern of eye movements. Gopher studied a task in which the subject is instructed to listen to both messages and to repeat target words that can be presented to either ear. When the target words are distinguished by a physical property (e.g., a word spoken by a male voice inserted in a message spoken by a female voice), subjects primarily fixate ahead, although they make an eye movement whenever a critical word is heard. When the critical word is defined by a semantic property (e.g., an animal name) the rate of eye movements doubles, and rhythmic alternations of small saccades become very frequent.

Gopher (1971) found that deliberate fixation to right or left can alter performance in a task of divided auditory attention. His subjects were asked to monitor dichotic messages for the occurrence of semantically defined target words. Occasionally, two target words were presented simultaneously. As will be shown in Chapter 8, subjects often detect only one member of such a simultaneous pair, and right-handed subjects most often respond only to the word presented to their right ear. This pattern was even more pronounced when subjects were instructed to fixate 20 degrees to the right of center. When they were instructed to fixate left of center, the imbalance between the ears vanished. The result could reflect either a shift in the spatial focus of attention or a temporary alteration of the normal pattern of cerebral dominance (Kinsbourne, 1970, 1972).

The relation between auditory attention and the direction of the gaze is an important source of cues in situations of social interaction (Argyle & Dean, 1965; Exline, 1963, 1971; Kendon, 1967; Strongman, 1970). People are extremely sensitive to eye-to-eye contact and show unusually high acuity in judging whether someone else is gazing directly at them (Gibson & Pick, 1963). The listener in a conversation tends to gaze directly at the speaker, and this gaze, which conveys continued interest, provides support for the speaker. The listener normally averts his gaze when he prepares to speak, probably indicating that he is turning attention to the preparation of his own message. The listener's averted gaze is often accepted as a tacit instruction for the speaker to fall silent.

The direction of the gaze aversion which accompanies the onset of active thought is highly consistent for different individuals and for different classes of problems. About half the population initially look to the right when they begin to think about a verbal problem, and the other half look to the left (Day, 1964, 1967a, b). Kinsbourne (1972) noted that movements to the left are relatively more frequent when subjects solve spatial problems than when they solve verbal problems, and he also showed significant differences between right-handed and left-handed subjects. Both observations suggest that the lateral movement may indicate a temporary preponderance of activity in one or the other hemisphere of the brain. Other investigators have studied various correlates of the preferred direction of the lateral eye movement. Thus, Bakan (1971) reported that left-movers are more hypnotizable (the correlation was 0.44), and he confirmed Day's observation that the EEG of left-movers has a prominent alpha component. Bakan and Shotland (1969) also showed that right-movers read significantly faster than left-movers and are less prone to interference on the Stroop test. Perhaps most surprising, a significant negative correlation was found between the eye movement tendencies of spouses (Day, 1967a); right-movers tend to marry left-movers!

Turning inward to think is also associated with a dramatic increase in the rate of eye movements (Lorens & Darrow, 1962), which contrasts with the inhibition of eye movements during attentive listening (Gopher, 1971). Antrobus, Antrobus, and Singer (1964) noted that both active thinking and deliberate attempts to suppress a conscious wish or fantasy are associated with a very high saccadic rate. Relaxed, passive, or wish-fulfilling thought leads to reduced motility. The frequency of blinks follows similar rules. These results suggest that changes of fixation and blinks punctuate changes of mental content, a conclusion which is also consistent with the observation that LSD causes a very high saccadic rate (Kohn & Bryden, 1965). It is notable that mental work increases ocular motility even in congenitally blind subjects (Amadeo & Gomez, 1966).

In summary, the involvement of eye movements in mental processes attests to the linkage between the eye and the focus of attention. Thoughts often "move" over a representation of space, and the position of the eyes tends to reflect the current direction of attention. Eye position also serves to label the direction of sensory attention, even in the absence of visual input, and this pattern of selective orientation may affect the allocation of auditory attention. Finally, the rate of eye movements often corresponds to the rate of thinking, even in the absence of any spatial component.

REVIEW

The three sections of this chapter were devoted to three types of eye movements, which were distinguished by the situations in which they occur: spontaneous looking in the absence of a specific task set; looking that serves to acquire task-relevant information; and looking that accompanies internal processing events.

Spontaneous looking is controlled by collative features of stimuli, such as novelty, complexity, and incongruity. The antecedents of these enduring dispositions are found in innate dispositions to orient toward contours and toward moving objects. The enduring dispositions that control spontaneous looking serve the function of information-seeking, rather than the function of pleasure-seeking.

Task-relevant looking was viewed as an allocation problem. Because the area of sharp vision is narrow, it must be directed to those portions of the field which are likely to be richest in relevant information. The decisions often require a sophisticated weighting of many factors, and they are made quickly, for the eye changes positions 3–5 times a second. The sequential allocation of glances is a highly skilled performance. The system generally makes decisions about the locus of individual fixations rather than about their duration, which is often quite stable. In complex visual discriminations, however, the duration of individual fixations may vary, within rather narrow limits, according to the demands of the task.

Finally, eye movements are a salient manifestation of the changing orientations which occur whenever the focus of thought refers to a direction in space. This orientation occurs even when it cannot possibly aid in the acquisition of new information. Movements of the eye also accompany, and perhaps influence, the balance of activity between the cerebral hemispheres, and the rate of eye movements often corresponds to the rate of mental activity.

5

Attention and Perception

The preceding chapter was concerned with overt orientations that reflect the allocation of attention. We now turn to the study of central mechanisms of selection and allocation. The present treatment identifies the allocation of attention to perceived objects with the figural process, which selects certain areas of the field as figure and relegates others to the background.

The first section outlines a model of some stages of perceptual analysis, and the second introduces a taxonomy of attention tasks. The remainder of the chapter is concerned with the explication of the processes of unit formation, figural emphasis, recognition, and perceptual interpretation, and with the relation of these processes to selective attention.

STAGES OF PERCEPTUAL ANALYSIS

The analysis of attention in this and in subsequent chapters will assume the model of perception illustrated in Figure 5-1. The figure traces the vicissitudes of a pattern of stimulation to which an observer

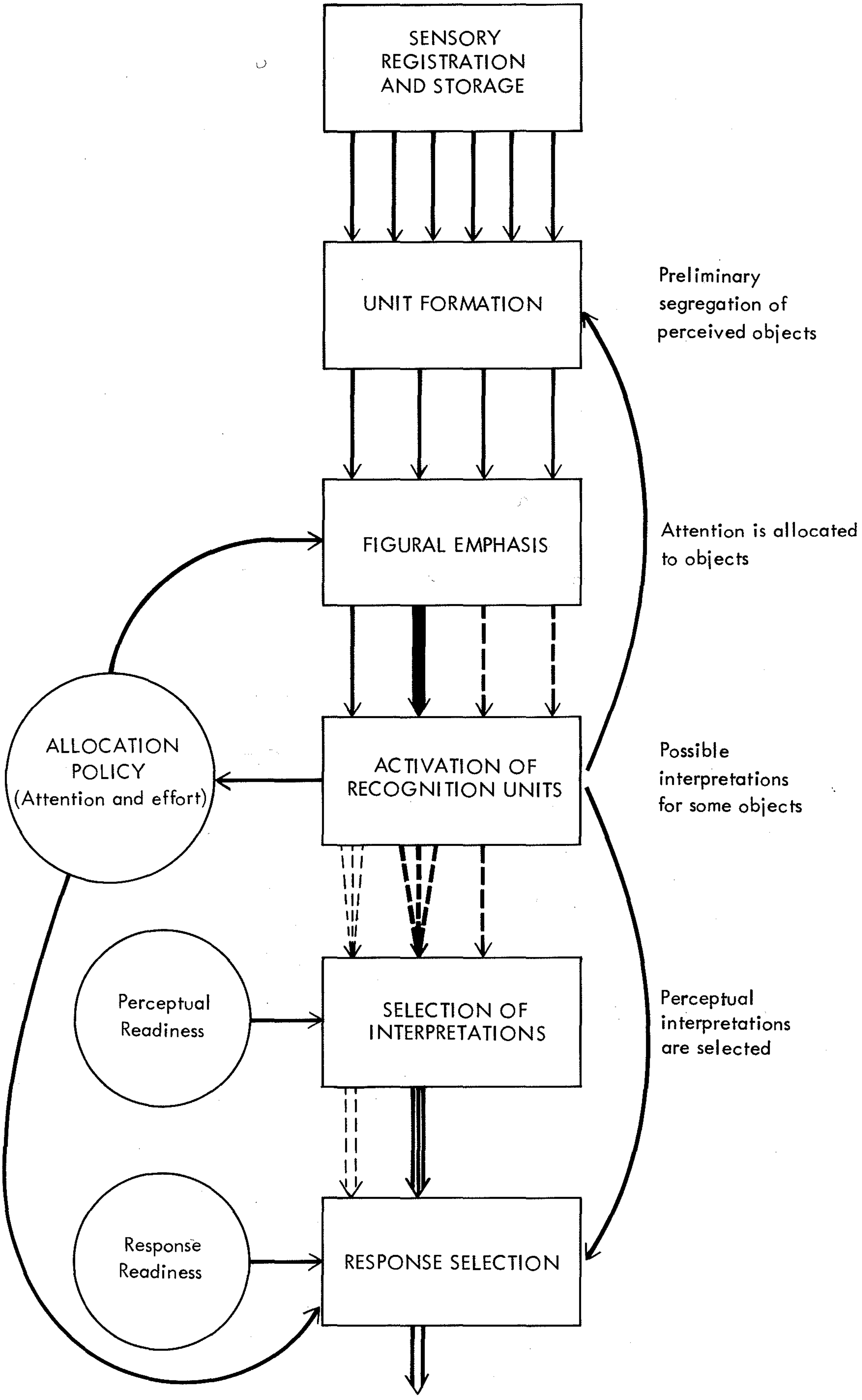

FIGURE 5-1
Schematic model for perception and attention.

is exposed, from an initial stage of sensory registration and temporary storage in sensory memory, through a final stage at which a response may be selected. The model assumes that an early stage of *Unit Formation* partitions the stimulus field into segments, or groups. The Gestalt laws of grouping describe the operation of this stage on visual stimuli. Similar rules of grouping operate in audition: for example, successive sounds that originate in the same place are more likely to be grouped as a unit than sounds from different places. These rules produce perceptual units that have a high probability of corresponding to distinct objects in the scene: a robot programmed to apply Gestalt laws of grouping to a photograph will usually segregate real objects. Units have both spatial and temporal aspects: grouping over space yields perceived objects; grouping over time yields perceived events.

Attention enters at the next stage, where some of the units isolated earlier receive greater *Figural Emphasis* than others. The decision made at this stage involves choosing the size of the relevant unit, and selecting the unit or units of that size which should be emphasized. Thus, the page, the line, the word, or the individual letter may be the relevant units, among which we select that word or that letter to which most attention will be paid.

The amount of attention that is allocated to a perceived object or event at this stage affects subsequent processing in several ways. Attended events are more likely to be perceived consciously, and more likely to be perceived in detail. They have a higher probability of eliciting and controlling responses, and they are more likely to be stored in permanent memory in a manner that permits intentional retrieval.

The next stage of processing is the activation of *Recognition Units.* These hypothetical structures are activated by the occurrence of a stimulus that possesses certain critical features. The activation of a recognition unit is a matter of degree. Activation is highest for a stimulus which has all the critical features, is presented at high intensity, and is attended. Inattention, degraded presentation, and a mismatch between the features of the stimulus and those of the recognition unit cause activation to decrease.

The graded output of recognition units is fed to a stage which selects *Perceptual Interpretations* for some of the perceived objects or events. Recognition units and interpretations are organized in dimensions and sets. The stage of selection of interpretations guarantees that no more than one interpretation is assigned to each object in each set or dimension. Thus, a homogeneous patch of color is not seen as both red and yellow, nor is it seen as both a square and a circle. A perceived object is normally assigned values on the dimensions of size, color, distance, direction and velocity of motion, and so forth. In addition, it may be assigned a meaning. Thus, the full perceptual interpretation of an object or event consists of a bundle of partial interpretations.

Selection of an interpretation is required because stimulation is normally ambiguous. Any stimulus event probably activates several recognition units in each set or dimension, although to different degrees. In addition, there are different degrees of *Perceptual Readiness* to make each of the possible interpretations at any instant in time. The interpretation which is selected is that for which the sum of readiness and activation is highest.

It is useful to assume a threshold below which no interpretation is made. Thus, a stimulus may fail to be fully interpreted if it was faint or did not activate any recognition for which there was sufficient readiness. Interpretations serve as input for subsequent stages of processing, including storage in permanent memory and the selection and control of responses. An uninterpreted event will have little or no effect on these stages.

The last stage shown in Figure 5-1 is that of *Response Selection.* In many experimental studies of attention, one of the multiple interpretations that is attached to an attended object controls the choice of a response. The subject in such experiments is usually constrained to make a response of a particular class, e.g., name a digit, identify a word, or evaluate the length of a line. These instructions induce a state of *Response Readiness,* making the appropriate responses more easily available. In addition, there may be differences in the degree of readiness for possible responses within each set.

The model shown in Figure 5-1 is not intended as a complete "model of the mind." It does not refer explicitly to various storage systems, and it does not deal with the initiation and control of covert and overt responses. It only distinguishes a few stages and operations which are essential to a treatment of selective attention in perception.

The allocation of attention affects events at two stages in the sequence of the information-processing chain in Figure 5-1. At the stage of figural selection, paying attention to some perceived objects in preference to others facilitates the activation of recognition units. At the stage of response selection, effort and attention are allocated to some responses in preference to others.

Two recursive paths are indicated in the model. The path leading from the stage of Activation of Recognition Units to the Unit Formation stage indicates that tentative recognitions can affect the segmentation of objects of perception. Another important path leads from the Activation of Recognition Units to the Allocation Policy and eventually back to affect Figural Emphasis. This recursive path was already mentioned in the context of the orientation reaction. It appears to play an important role in search tasks that will be discussed later in this chapter.

Conscious perception can be identified with the selection of interpretations. This stage is sometimes bypassed in the control of action. For example, there is suggestive evidence that the latency of conscious perception is about the same as the latency of overt responses in a simple reaction-time task (Kahneman, 1968). If this is the case, then simple responses cannot be dependent on prior conscious perception (Fehrer & Raab, 1962). The possibility of bypassing the stage of conscious perception is indicated in Figure 5-1 by the arrow leading directly from the Activation of Recognition Units to Response Selection.

TAXONOMY OF SELECTIVE ATTENTION

According to the model shown in Figure 5-1, attention is allocated at two stages: figural emphasis and response selection. The two possibilities are related to a distinction drawn by Broadbent (1970, 1971) between *stimulus set* and *response set.* Stimulus set defines the relevant stimuli by a physical characteristic, which permits these stimuli to be analyzed in more detail than other stimuli. Response set restricts the vocabulary of possible responses. When a subject is instructed to read words printed in red and ignore other words, he adopts a stimulus set. When instructed to read digits and ignore other words, he adopts a response set.

A more elaborate classification scheme for attention tasks was proposed by Treisman (1969), who distinguished four types of selection: of inputs, targets, analyzers (or attributes), and outputs. Table 5-1 illustrates this scheme by examples of four tasks that a subject may be asked to perform, given a particular stimulus array.

(*1*) Selection of *inputs.* The relevant and irrelevant stimuli are discriminated by an obvious physical characteristic, allowing the subject to adopt a stimulus set. Broadbent (1958, 1971) calls this type of early selection *filtering.* An auditory example of input-selection task could be: "Listen to the message that comes from the left; ignore other messages." According to the model introduced in the preceding section, the selection of inputs is mediated by the allocation of attention to the relevant inputs at the stage of figural emphasis

(2) Selection of *targets.* Here the subject is instructed to search for a designated target. The distinction between selection of inputs and selection of targets is that the relevant items are rare and relatively

difficult to find in the latter task. However, the mechanism of selection appears to be similar in the two cases.

(3) Selection of *outputs* of perceptual analysis. In the example of Table 5-1, the numerals are not distinguished from other words by any obvious physical characteristics. Consequently, the relevant items can only be selected after they are interpreted in perception. In Broadbent's terms, this task involves a response set, since the relevant items are defined by a common category of responses rather than by a shared physical attribute.

(4) Selection of *attributes*. In the example of Table 5-1, the relevant attribute is letter-type. This task involves response set, since the vocabulary of allowable responses is sharply limited. In the model of Figure 5-1, the task is performed by allocating attention to one of the responses elicited by each item (describing type) in preference to other responses (e.g., reading the word).

Discriminations are made at several stages of perceptual processing: *pre-attentive* discriminations control unit formation and figural emphasis (Neisser, 1967). Additional discriminations, achieved at the level of perceptual interpretations, guide the selection of responses. Most tasks involve discriminations at both levels (von Wright, 1970). For an example, consider task 1 in Table 5-1. One must first find the capitalized words, then read them. Figural selection (finding) is guided by a discrimination of letter size, while response selection is controlled by discriminations of letter shape.

For another example, consider the two questions "What is the bottom word in the array of Table 5-1?" and "Where is the word five?" Both

TABLE 5-1
A classification of attention tasks.

Stimulus	*Task*	*Labels*
cat EIGHT TABLE seven TWO dog BAT chair BOOK egg time PLANT soon fish PIANO door FOUR five	(1) Read the capitalized words.	Selection of inputs; filtering; stimulus set.
	(2) If the word "egg" is in the array, say it aloud.	Selection of targets or tests.
	(3) Describe the type in which each word is printed.	Selection of analyzers; attention to attributes.
	(4) Read the digits.	Selection of outputs; response set.

questions eventually refer to the same object, the word-five-that-is-printed-at-the-bottom, but the sequence of operations that lead to this object are different in the two tasks.

The reader will probably agree that it is easier to find the word at the bottom and read it than to find the "five" and report its location. The sequence of operations on attributes is important because the attributes which allow the most effective control of figural emphasis are not the same as the attributes to which responses are most easily attached. The example illustrates the general rule that it is easy to direct attention by the attribute of location, and easy to control the final response by the attribute of shape. It is also easy to control visual attention by the attribute of color (Uleman & Reeves, 1971; von Wright, 1970; Williams, 1966).

UNIT FORMATION

Some examples of unit formation in vision are shown in Figure 5-2. The most compelling of these examples is (A), which is interpreted unambiguously as an object over a background. Note that a grouping process is required to segregate the object as a single unit. Note also the hierarchy of the grouping organization: the object in panel A is a unit, which is included in the larger unit of the panel, which is included in turn within the larger unit of the entire figure, and so on. Within panel A, the background may be considered as a group, but each of the small objects within it provides another natural unit.

Other panels of Figure 5-2 illustrate various determinants of grouping, which differ in their effectiveness. In panel B, most observers see rows, rather than columns, by an effect of *similarity*. In panel C, columns are seen, because *proximity* overcomes the effect of similarity. Panels D and E show that the discriminability of elements determines the quality of grouping. Grouping is distinctly "better" and more definite in panel D than in panel E.

Finally, compare panels F, G, and H. In these panels, the elements in three segments of the circle share a feature that could distinguish them from the elements in three other segments. A rather clear organization emerges in panel F, but less in panels G and H. The variable of shape in panel G and the variable of letter orientation in panel H do not suffice to integrate the three similar segments into a single form. The groupings that spontaneously emerge in these examples are more restricted, and even an intentional effort to "see" the larger pattern generally fails.

There are other differences among attributes in the degree to which

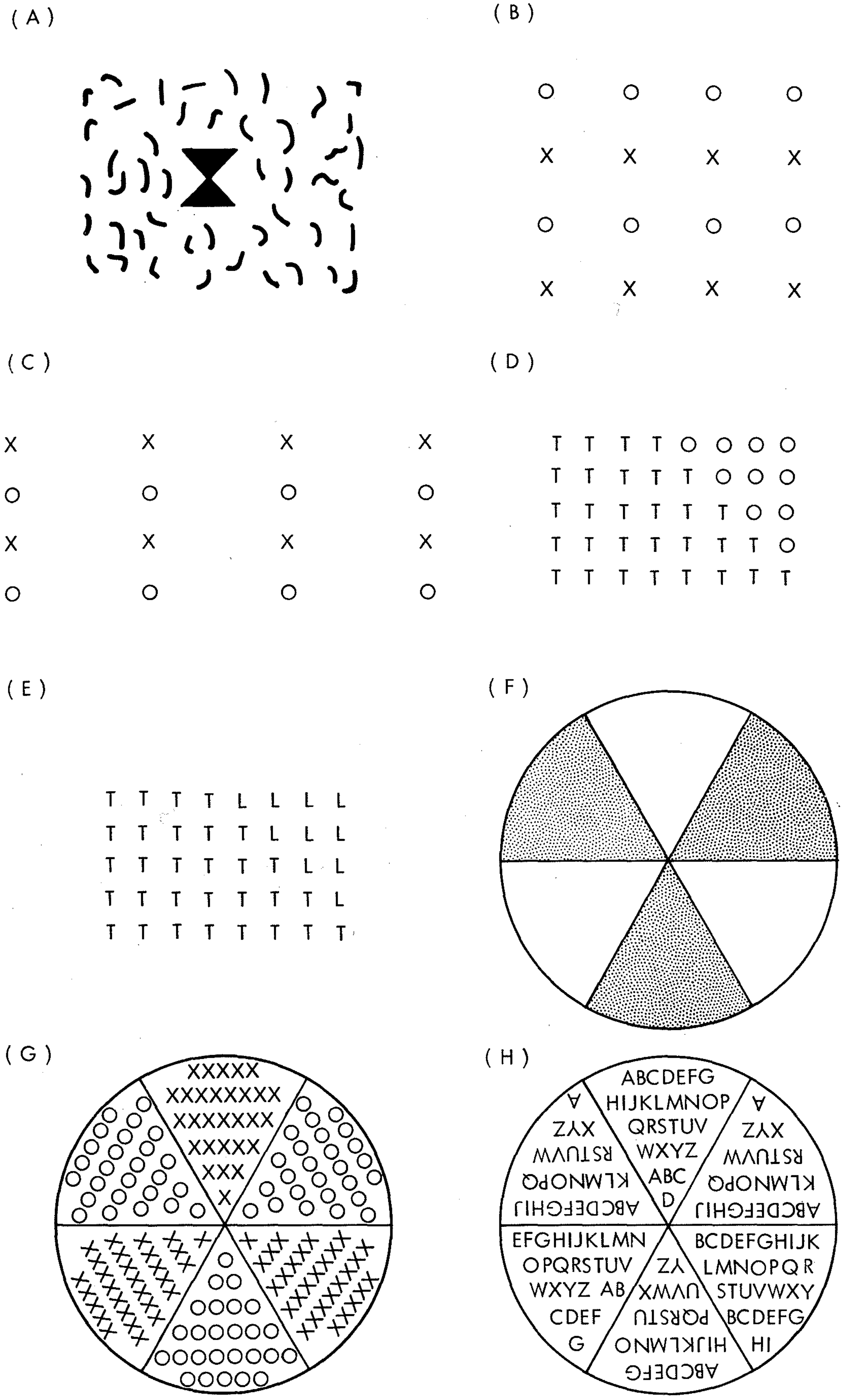

FIGURE 5-2
Determinants of grouping.

they allow for similarity grouping: similarity of shape and similarity of slope, for example, are less effective than similarity of color or brightness. The properties that provide strong units also allow for the effective control of attention, because attention is most easily directed toward a natural perceptual unit. Thus, Williams (1966) and von Wright (1968, 1970) noted informally that effective search is possible within the visual field only when all potential targets share a physical characteristic (e.g., color) which permits them to be segregated into a figural group.

An experimental demonstration of the relation between grouping and search was offered by Beck (1972). He showed subjects an array consisting of a majority of elements of one kind, and of scattered elements of another kind. Some subjects were asked to count the minority elements. Other subjects rated the ease with which the minority elements were segregated as a perceptual group. As expected, it was easy to count elements that made up "good" groups. In agreement with earlier work (Beck, 1966, 1967; Olson & Attneave, 1970), a difference in overall slope (e.g., tilted T's in a field of upright T's) provided a better basis for grouping than differences in line arrangement with constant slope (e.g., L's in a field of T's). Correspondingly, the tilted T's were also easier to find and count. The relation between grouping and counting is strong: it is easier to count the O's in panel D of Figure 5-2 than the L's in panel E.

Beck (1972; Beck & Ambler, 1972) proposed that grouping is often based on the detection of differences between elements in peripheral vision, prior to a focusing of attention. Furthermore, he suggested that pre-attentive and attentive discriminations follow different rules. Thus, sensitivity to differences in overall slope is relatively greater in pre-attentive discriminations, or when attention is divided among many objects than when attention is focused. A tilted T is more discriminable from an upright T than is an L, but only when several background stimuli are shown. When a single form is shown in peripheral vision, the tilted T and the L are equally discriminable from an upright T. Further, when an array of letters is shown briefly, then masked, the tilted T is more discriminable than the L when the masking stimulus quickly erases the array, but not when the subject is given more time to redirect his attention (Beck & Ambler, 1972).

Beck's work suggests that the grouping process is controlled primarily by the detection of similarities and differences among the elements simultaneously present in the field. His analysis helps explain the observation noted earlier, that different attributes are most effective in controlling attention and in controlling responses. The discrepancy could be related to the relative ease with which one makes simultaneous or successive discriminations. Attributes that allow for easy simultaneous discriminations will be effective in controlling attention, because simultaneous discriminations are involved in unit formation and in figural emphasis. Attributes that permit accurate successive discriminations should be most effective in the selection of responses.

The effects discovered by Beck provide strong support for Neisser's (1967) suggestion that *pre-attentive* mechanisms carry out the task of sorting and organizing the field prior to the operation of focal attention. These discriminations are not guided by the perceiver's intentions. It is not known whether they vary with available capacity. Pre-attentive discriminations refer to obvious physical features, but it is inappropriate to assume, as some authors have done, that discriminations of physical features are always pre-attentive, and that only higher-order properties are analyzed attentively (Ellis & Chase, 1971). Beck's work indicates that discriminations of physical features occur at both the pre-attentive and attentive levels, but follow different rules at the two levels.

Neisser (1967) suggested that pre-attentive discriminations are relatively crude. Indeed, the strongest grouping effects are controlled by proximity or by similarity of obvious physical features. There are indications, however, that perceived units sometimes depend on more complex analyses of the stimulus, even including semantic decoding. Speech, for example, is perceived as consisting of discrete words, although a physical analysis of the sounds often reveals no pause between the end of one word and the beginning of the next. Fixate above the central O in THEDOGATE and you may see figural areas of different size, but most often the meaningful unit "dog" (Osgood, 1953). Finally, although the THE of OFTHEOX makes a poorer perceptual unit than the XXX in --XXX--, it is easier to segregate than the THE in BATHERE, because of the competition of coding responses in the latter case. In the model of Figure 5-1, these effects are represented by the arrow leading from the recognition units to the grouping stage.

Treisman (1970) has reported an auditory experiment in which a physical cue (ear of origin) becomes effective in segregating a perceptual unit only when it interacts with existing language habits. She presented pairs of computer-synchronized auditory items, either binaurally (both sounds to both ears) or dichotically (one sound to each ear), and her subjects often responded with a mixture of phonemes from the two stimuli, even in dichotic presentation (e.g., the response TEV to the stimuli TAV and SEM). Surprisingly, the frequency of these confusions was about equal in dichotic and in binaural presentation when the two stimuli were both nonsense syllables. However, dichotic presentation did reduce confusions when a nonsense syllable was presented to one ear and a digit to the other. The very precise synchronization of dichotic inputs apparently provides a powerful stimulus for fusion, which can only be overcome when one of the separate inputs activates a recognition unit.

So far, this discussion of unit formation has reflected the historical emphasis on spatial grouping in vision. However, grouping processes operate in other sense modalities, and grouping occurs over time as well as in space. Temporal grouping isolates events, rather than objects. Michotte (1963) and Heider and Simmel (1944) have described some compelling examples of such grouping. Imagine a scene with two white squares separated by a gap. The left square starts to move to the right; it reaches the right square and stops; within 100 milliseconds, the right square starts to move to the right. This sequence is almost invariably perceived as a single event, in which the left square "hits" the right square and causes it to move. Audition, of course, is a temporal sense and auditory grouping is largely temporal grouping. The musical or the verbal phrases function as perceptual units. Some factors of grouping, such as proximity and similarity, are common to the formation of spatial units in vision and of temporal units in audition: sounds tend to be grouped if they originate from the same location, or if they share certain physical characteristics (Broadbent, 1971, Chap. 4).

The basic identity of grouping processes over space and time has not always been recognized, probably because it is difficult to speak of events and of objects in the same terms. As a consequence, a harmful distinction has been introduced between closely related variants of attention. Thus, visual attention is often described as the selection of stimuli or objects, while auditory attention is commonly described as the selection of a "channel." Treisman (1969) has attempted to overcome this difficulty by using the neutral term "selection of inputs." The terms of the present treatment, units and figures, suggest visual images—but the concepts are more abstract, and they can be applied alike to different modalities, and to units over time and space.

FIGURAL EMPHASIS

The spontaneous division of the field into figure and ground is a basic fact of perceptual experience. It is also a prototype of a purely central process of selection which does not depend on orienting movements of the head or eyes. When part of a flat picture "stands out" in perception, it is seen as figure over its background. The subjective experience of attention is often described in the same terms: the attended object "stands out."

Panels A–D of Figure 5-3 illustrate the familiar distinction between figure and ground. In all panels there is a clear organization of the field into segments or groups, of which one predominates and is seen as figure. The main manifestation of the figural character of an area is that

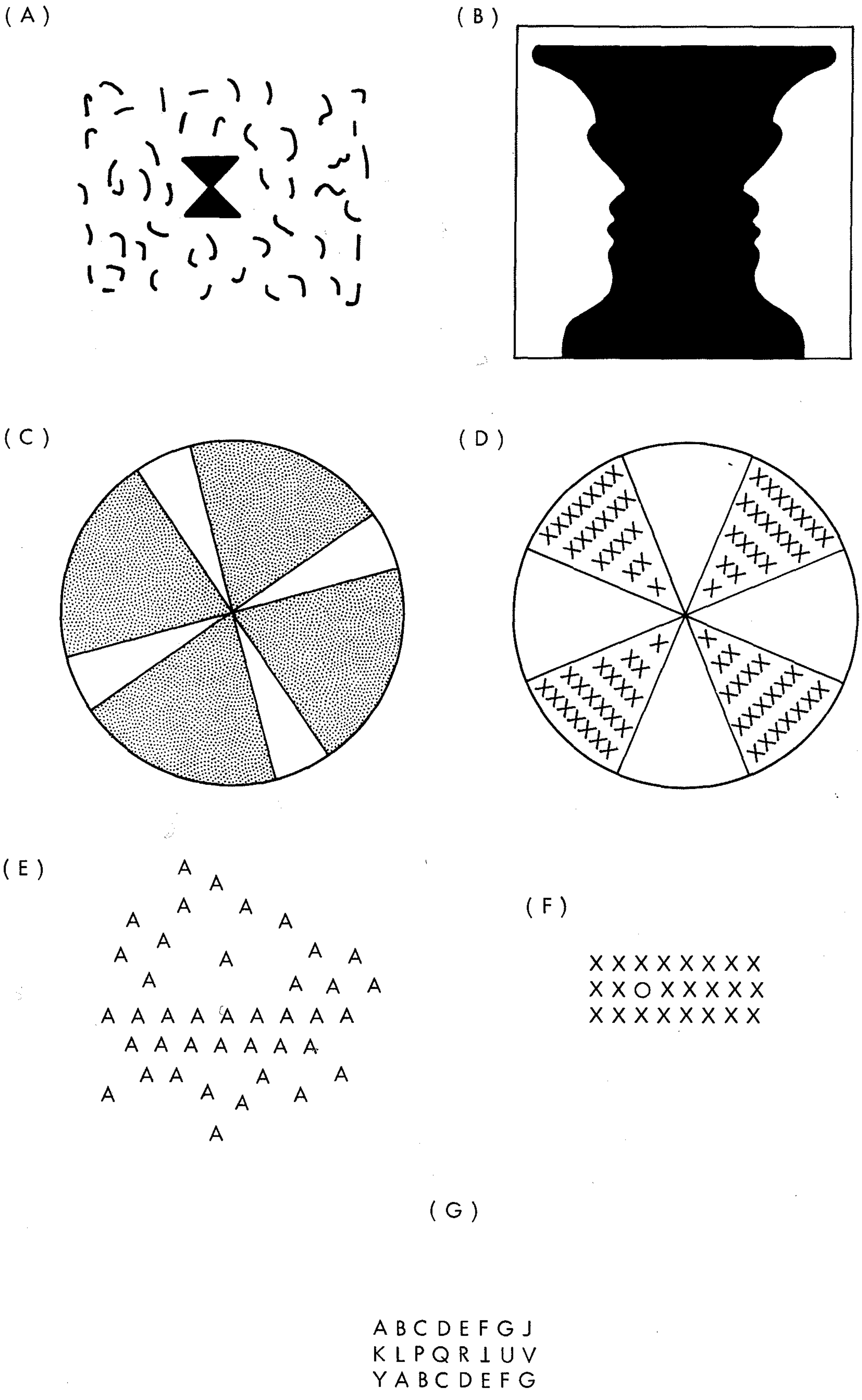

FIGURE 5-3
Determinants of figural emphasis.

its bounding contours are perceived as belonging to it rather than to the background. In addition, there is a depth effect: the figure appears closer than the ground. Finally, the figure is more impressive than the background: it has "thing-character," whereas the background has "stuff-character." Note this change of character when the figural organization in panel B reverses.

In view of these differences between figure and ground, it is not surprising that elements and aspects of a picture are more likely to be noted and remembered if they belong to the figure than if they belong to the ground (Weitzman, 1963). Similarly, Luria (1961) reports that children find it much easier to respond to information conveyed by the figure than to information conveyed by the background. In general, then, the figure is what perception is about.

In the age of introspection in psychology, attensity, or vividness were the terms for the attribute that a sensation gains when it is attended to (Titchener, 1908, 1915). Titchener identified attensity with clearness, and sharply distinguished this attribute from intensity. Thus, a baby's whimper can be heard with high attensity over the roar of a storm. It requires little introspective indoctrination to agree that the figures in panels A–D are perceived with much greater attensity than are the backgrounds.

In each of the other panels of Figure 5-3, there is also one area of the field that has greater attensity, or greater *Figural Emphasis* than others. The illustrations provide examples of several determinants of figural emphasis. These determinants can be divided into three sets, similar to the sets of factors that control eye movements: (1) innate dispositions that operate on physical characteristics; (2) collative factors; and (3) selective intentions.

(*1*) In general, as shown in panel C of Figure 5-3, the smaller object tends to be seen as figure, and the larger object as ground (Koffka, 1935). There also appears to be a strong tendency to favor objects in warm colors, such as red or yellow, over cool colors, such as blue or green. Moving objects are particularly likely to be seen as figure. This combination of rules must have helped our distant forebears perform the vital task of detecting prey and predator on a background of sky and vegetation. Contour-rich (panel D) and isolated stimuli (panel E) are also favored, as are bright objects. Because the same features of stimuli control both the fixation of the eye and the selection of a figure, the figure is usually fixated in preference to the background. Figural selection and fixation are functionally independent, however, since a deliberate fixation on the ground does not always reverse the prevailing figural organization.

(2) Collative factors are illustrated in panels F and G, where the odd element tends to "stand out," as does the CAPITALIZED word in this sentence. There may be an impression of three-dimensionality, although not as pronounced as in panels A–D.

(3) The effect of intentions is easily observed by deliberately selecting an element in any of the panels, e.g., a particular letter in panel G. One may choose a larger unit, but at a certain cost in the experience of attensity. It is this feature of the experience of attention which suggests the frequently used metaphors of "a beam of light of varied width" (Hernandez-Peon, 1964) or "a lens of variable power" (Eriksen & Rohrbaugh, 1970; Eriksen & Hoffman, 1972).

The subjective experience of selective attention to inputs is closely related to the experience of figural emphasis. It is therefore reasonable to describe selective attention as a consistent emphasis on a class of perceived objects or perceived events in preference to others. Thus, paying attention to the red objects in a scene means that these objects will be seen as figures, all together or one at a time. Listening to the radio while one's children are fighting means that the announcer's voice must be heard as figure, the children's screams as background.

In general, we succeed superbly in such tasks. Indeed, the main limitation on our ability to control attention occurs at the stage of unit formation. If a list of digits and a list of letters are recorded in such manner that one hears both messages in the same voice over the same speaker, it is virtually impossible to attend selectively to the digits, because successive digits do not form a distinct unit, while the simultaneous digit and letter tend to fuse. The same experiment may be carried out in vision: if a mixed array of digits and letters is briefly exposed, it is almost impossible to read only the digits, again because of a failure of the digits to constitute a group. In contrast, it is possible to read items printed in red or listen to a message spoken by a woman and ignore a simultaneous message spoken by a man. Finally, it is quite easy to attend to the voice heard from the right, or to the top row of a visual array. Where the unit formation stage provides several "good" groups or units, it is usually possible to deliberately select one of them for the role of figure.

The decision to select some stimulus for special emphasis can be made before the stimulus is actually shown, with immediate effects on how the stimulus is perceived. Perhaps the most compelling evidence for this conclusion is the phenomenon of prior entry. When a subject is told that he will see a flash of light and hear a tone at about the same time, and that he is to attend especially to one of them, the perception of simultaneity is biased. The stimulus that is attended to is perceived as occurring relatively sooner than the other. Consequently, the two appear to be simultaneous when the attended stimulus is actually shown later than the other (see p. 137).

THE CONTROL OF FIGURAL EMPHASIS IN SEARCH

Eriksen and Collins (1969a) have recently described an impressive demonstration of a figural effect in a search task. They used a visual display to present the digits 1–9 in rapid succession, omitting one digit of the sequence on half the trials. On each trial the subject reported whether the sequence was complete. Two conditions were compared: a precuing condition in which the subject was told in advance which digit, if any, would be omitted, and a postcuing condition in which the same information was given only after the exposure. Performance was vastly better in the precuing condition, where subjects set themselves to look only for the designated target. As a result of this set, the target digit "stood out" clearly in perception whenever it was shown. The effect was so strong that subjects confidently asserted that the target had not been shown whenever it failed to "stand out" perceptually, and they were usually right, even when the digits were presented at the fast rate of one item per 50 milliseconds. In the postcuing condition, on the other hand, subjects achieved perfect performance only if they could perceive and identify each successive digit, and this required at least 200 milliseconds for each item.

The experience that a designated target tends to become figural over an indistinct background has been described in other studies of visual search. In a paradigm developed by Neisser (1963, 1965; Neisser, Novick & Lazar, 1963), subjects are instructed to look for a particular letter or for any one of several letters in an array. The subject scans the array, line after line, and the time that he needs to decide that a line does *not* include the target is measured by plotting the latency of the detection of the critical line against the position of that line on the page. For example, if a target on line 20 is detected in 16.5 seconds, and a target on line 30 is detected in 24.5 seconds, then the time-per-line must be 0.8 seconds. In some of Neisser's experiments, highly practiced subjects could scan a line of four letters in as little as 0.1 second, but this high speed was achieved at the cost of many errors of omission. Under these conditions, Neisser's subjects reported that the non-target items were seen as a mere blur, while target letters appeared to jump from the line.

As might be expected, the speed of search depends on the ease with which the target can be discriminated from its background. Even after prolonged practice Neisser's subjects found it more difficult to search for a Q in an array of rounded letters (C, G, O, etc.) than in an array of angular letters (X, M, K, etc.). The difficulty of discriminating target from background is also increased when the background elements are heterogeneous. This effect was observed in a series of studies by Gordon (1969; Gordon, Dulewicz & Winwood, 1971).

Skill in the performance of search tasks is acquired slowly (Rabbitt, 1964, 1967). When searching for multiple targets, the observer gradually develops the ability to respond to critical features that the targets share. Thus, Rabbitt (1967) showed that subjects trained to discriminate the two target letters C and O from the irrelevant set (A, E, F, H, I, K, L) transferred readily to a discrimination with the same targets and a new irrelevant set (M, N, T, V, W, X, Y), because both irrelevant sets consisted of letters with no curved segments. Negative transfer was obtained when the new irrelevant set consisted of curved letters (B, D, G, P, Q, S). Rabbitt agreed with Neisser that irrelevant items are not analyzed in as much detail as are the relevant targets. In the terms of this chapter, the targets are emphasized more than other items.

It is not clear whether the figural emphasis on the target occurs directly, or through the mediation of recognition units. Under some conditions, the stage of figural emphasis can be preset so that a stimulus which possesses certain features will gain emphasis. This mechanism is involved in the selection of inputs. Alternatively, a stimulus may first activate the recognition unit for a target, and this tentative recognition would cause the emphasis. The recursive path of attention control was discussed earlier in the context of Sokolov's neuronal model theory of the orientation response. Collative properties such as novelty or incongruity can only affect perception through such a path, because these properties arise from a mismatch between stimuli and expectations: the comparison of stimuli to expectations requires the participation of recognition units. A similar mechanism appears to be involved in the control of eye movement: as was shown in Chapter 4, the decision to have a closer look at a target is triggered by a rapid evaluation of how much information was acquired in the last fixation. An evaluation of information can also lead to the eye lingering slightly on a single fixation. These decisions which occur between saccades must be completed within 125–175 milliseconds, although they require complex computations in the recognition system.

In general, then, the recursive path of attention control is involved when the initial analysis of a stimulus does not yield a sufficiently detailed and complete perceptual interpretation. This may occur with novel or incongruous stimuli, and also in some search tasks. Neisser (1967) mentioned that subjects who were looking for several targets at once often became aware that they had detected a target before they knew

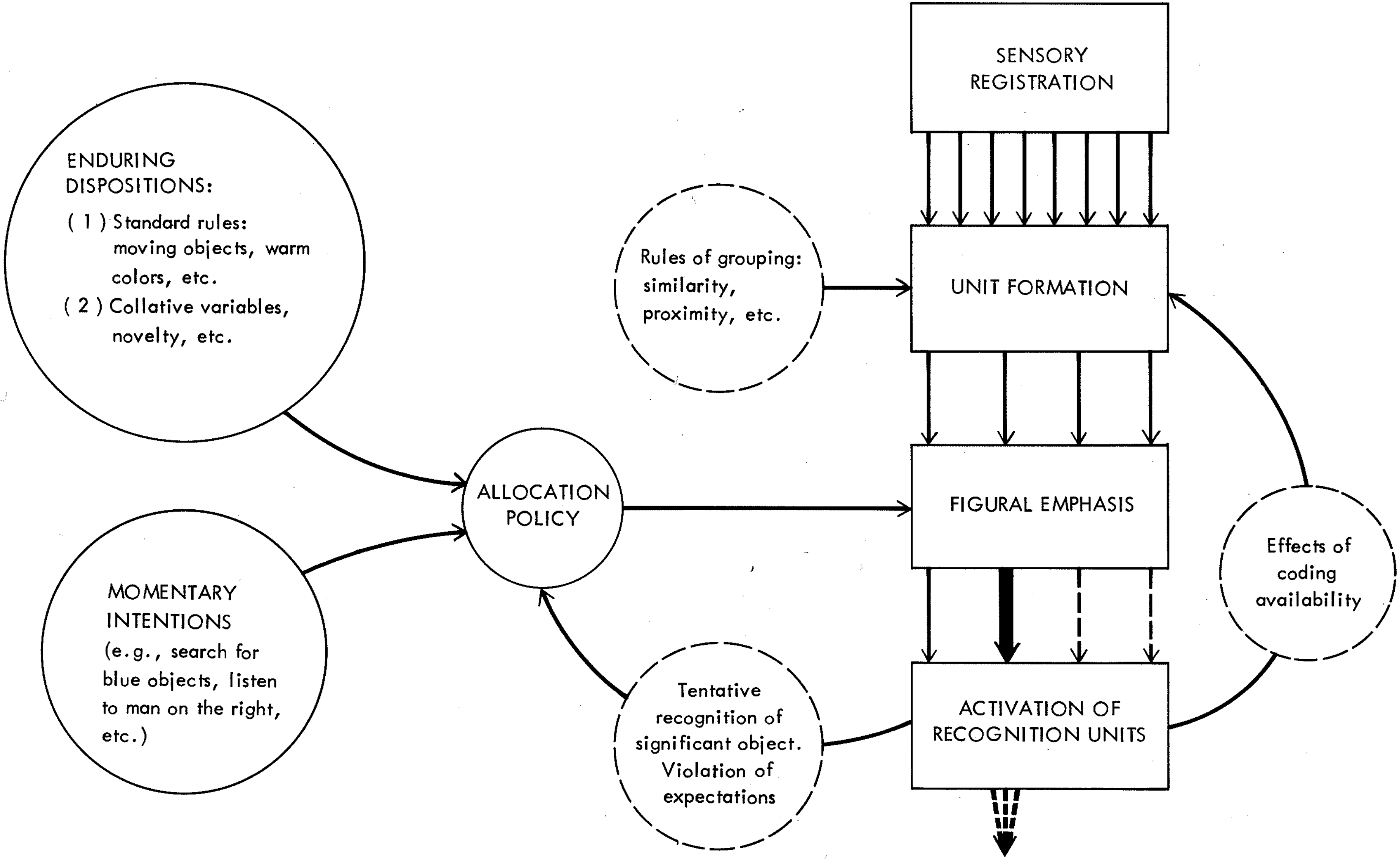

FIGURE 5-4
Attention, grouping, and figural selection.

what it was. This experience would be expected if a recursive path is involved. Thus, the observation that a target "jumps" from the background does not prove that the target was detected pre-attentively (Cavanagh & Chase, 1971). It is possible that the rapid rate of scanning in search provides a degraded visual input which is sufficient to weakly activate some recognition units, but is not sufficient to provide complete perceptual interpretations. The activation of the recognition unit corresponding to a target could cause additional capacity to be allocated to the relevant object, which would then become figural.

A study by Lawrence (1971) provides suggestive evidence that it may take appreciable time for a stimulus to call attention to itself. Subjects were shown a series of words which were successively presented in the same place. They were instructed to detect and read the one word in the series that was printed in capitals. Although subjects were usually very confident of their answers, they erred quite frequently by reporting a word that actually appeared after the target. This result is consistent with the assumption of a recursive loop. If the redirection of attention takes time, the word that initially called for attention will have been replaced by another before the cycle can be completed. However, the recursive loop could not have been involved in the experiment of Eriksen and Collins (1969a) that was described earlier, because the rate of presentation was too fast. At present there is simply not enough information about the conditions under which the control of attention is direct or recursive, although there appears to be sufficient evidence that both modes of control are sometimes adopted.

It appears reasonable to assume that the case in which a stimulus calls attention to itself is not fundamentally different from the case in which attention is directed by a cue. In a classic study, Averbach and Coriell (1961) analyzed the effect of a cue which indicated the location of a target in a complex tachistoscopic display. The warning cue was fully effective only when it preceded the display by 100–200 milliseconds or more. Thus, the redirection of attention appears to require that amount of time. Eriksen and Collins (1969b) later confirmed this measurement, with a procedure which eliminated possible artifacts of eye movements.

Space is involved, as well as time, in the control of attention. It is difficult to direct attention to a specific target in a crowded field. When a complex display is shown in the tachistoscope, a common type of error is the report of an item adjacent to the designated target (Eriksen & Rohrbaugh, 1970). This adjacency effect is much greater when the indicator is presented simultaneously with the target than when it precedes the target by 200 milliseconds. When the presentation of the array and the indicator is simultaneous, 100–200 milliseconds may be needed to direct attention to the target. By that time the display has been removed, and attention must be directed toward a fading representation. The frequency of adjacency errors indicates that spatial confusions are likely to occur in that case. These difficulties in "addressing" a target are increased both by crowding the items and by presenting a large number of items. Differences in reaction time as a function of addressing difficulties can be found even with clearly visible stimuli (Eriksen & Hoffman, 1972).

A particularly impressive observation was reported by Snyder (1972), who found adjacency errors even when the relevant target called attention to itself. Subjects were briefly shown a display of 12 different letters. One of these differed from the others, in color, in orientation, or by being fragmented. The subjects were required to report the odd letter. In many cases they erred and reported one of the letters adjacent to the target. This result provides strong evidence for recursiveness in the control of attention.

The examples that have been discussed so far were all visual, but the concepts of grouping and figural selection apply to other modalities as well. There is a clear experience of grouping in audition, both in space and over time. There is also an experience of figure-ground organization: as we listen to a concerto, the soloist often provides the figure, and we can also deliberately choose to attend to one group of instruments when the orchestra is playing.

The main conclusions of the preceding discussion of unit formation and figural emphasis are illustrated in Figure 5-4. The figure suggests that the process of figural emphasis should be viewed as the allocation of effort, capacity, or attention to the perceptual elaboration of some perceptual units in preference to others. The allocation policy is governed by enduring dispositions and by momentary intentions. As was the case in the control of eye movements, the enduring dispositions that control figural selection are of two types: standard rules that allocate attention when certain physical characteristics are detected, and collative features such as novelty or significance. The standard rules can be applied before the stimulus information makes contact with recognition units. Collative variables, on the other hand, can only affect figural selection through a recursive path.

The analysis of figural emphasis as a special instance of allocation of attention implies that perceptual processing draws on the limited capacity system that was discussed in Chapters 2 and 3. This conclusion is supported by the frequent observations of perceptual deterioration in a crowded and complex field (Eriksen & Lappin, 1967; Eriksen & Rohrbaugh, 1970; Keeley, 1969; Mackworth, 1965; Rummelhart, 1970). In an important study, Sperling et al. (1971) showed that information is extracted at approximately the same overall rate from arrays of varying complexity, and also that the processing of different elements in an array is carried out in parallel. Thus, the same total processing capacity is allocated, in different ways, to simple and to complex arrays. The relation between perceptual processing and the non-specific capacity is most clearly established by the observation that perception is impaired during mental effort (Broadbent & Gregory, 1963; Kahneman, 1970; Kahneman, Beatty & Pollack, 1967; Shulman & Greenberg, 1971). The detection and identification of brief or faint stimuli deteriorate when attention is withdrawn from perceptual elaboration to other activities. The vulnerability of perception to the competition of other activities indicates that all draw on a common pool of capacity—or attention.

THE ORGANIZATION OF RECOGNITION UNITS

The concepts of recognition units and perceptual interpretations are applied in a very broad sense in the present treatment. They refer to the perception of features of objects, such as size, shape, or color, as well as to the recognition and implicit naming of objects. The recognition system includes many functionally independent replicas of each recognition unit. This duplication is illustrated by our ability to see the pattern XOXXX. If there were a single X-detector, we would see an "O," paired with a single "X" of unusually high intensity! Some recent theories of speech-recognition, such as the logogen model (Morton, 1970a) do not include this duplication feature, and propose that a single logogen corresponds to each word-meaning. This assumption may or may not be valid with respect to the recognition of meanings. It is clearly not valid with respect to visual recognitions.

The recognition units appear to be organized in dimensions and in levels. The presentation of a stimulus normally causes activation of several units in each of these sets, and the role of the selection stage is to choose no more than one interpretation from each set. Thus, a single size, color, shape, and semantic meaning will eventually be perceived, although many more possible percepts may have been implicitly considered and rejected by the system.

Recognition units at several levels can participate in perceptual interpretation. A salient example is the effect of word context on letter recognition (Reicher, 1969; F. Smith, 1969; Wheeler, 1970): when a subject is shown the word WORK in the tachistoscope, and is asked if the last letter of the word was D or K, he does better than if the initial stimulus was GORK. The effect is particularly surprising, of course, because both WORD and WORK are words. How could the redundant initial letters aid in the discrimination?

A possible interpretation of this result is that sensory information activates recognition units both at the level of individual letters and at the level of words. Because the signal is faint and the recognition system is noisy, it may happen that the recognition unit for WORK is activated more than the recognition unit for WORD, while the separate units for the letters K and D are activated equally. If the recognition units at the word level are in contact with the selection of interpretations for individual letters, the recognition of a letter within a word will be superior to the recognition of the same letter in a nonsense syllable. In addition to the recognition units for letters and for words, there is evidence for units at the level of the spelling pattern (Gibson, 1965), the syllable (Smith & Haviland, 1972), and perhaps at other levels in the parsing of printed words (Spoehr & Smith, 1972). Recognition units at all these levels could collaborate in the selection of an interpretation at any level, e.g., reading a whole word or identifying a single letter. There is no compelling reason to assume that the units at the various levels are arranged in series, so that the output of one is the input for the other. An essentially parallel organization appears more plausible, in an overlearned skill such as reading.

The organization of recognition units has been extensively studied in two major paradigms: search and speeded judgments of sameness or difference. Posner (1969, 1970; Posner & Mitchell, 1967; Posner, Lewis & Conrad, 1972) has contributed several detailed analyses of this problem. The main tool that he employed is a same-different judgment with different rules. For example, a subject may be instructed to press the "same" key only when two stimuli have *physical identity*. He then responds "same" when exposed to the pair of letters a-a, but he responds "different" for the pair a-A. In the condition of *name-identity*, the correct response for a-A would be "same." In the condition of *rule-identity*, the correct response for a-U could be "same," because both are vowels, while the correct response for a-B would be "different."

A question of central interest is whether the different "codes" for a stimulus are elicited in parallel or serially. For example, the three instructions call for different codes of the stimulus "a": as a visual shape (for the detection of physical identity); as a letter name (for name identity); and as a vowel (for rule identity). Are the three codes generated in sequence? Note that the inferences that may be drawn from reaction-time data are not symmetric: if judgments under two instructions are equally fast, this provides evidence for independence of the corresponding codes. On the other hand, a difference of reaction-time does not provide equally strong evidence for a serial-dependent production of the codes because of the possibility that the two codes are generated in parallel, but at different speeds. Posner (1969) presented considerable evidence that the visual code and the name code for letters are in fact produced in parallel, although the production of the name code is slower. In the terms of the present chapter, this means that the visual letter "a" simultaneously activates at least two recognition units: a unit that is specific to the lower-case "a," and a unit for which both the lower-case and the capital forms are appropriate stimuli.

The conclusion that two physically distinct stimuli such as "a" and "A" can make contact with a common recognition unit without the mediation of prior recognitions is of fundamental importance, because it contradicts a common view of perception as consisting of the sequential production of increasingly abstract codes for a stimulus.

From the conclusion that "a" and "A" activate a common recognition unit, there is but a small step to the idea that all numerals may activate a recognition unit, and all letters another. Evidence from both reaction time (Posner, 1970) and visual search (Brand, 1971) indicates that this is the case. In contrast, there seems to be no common recognition unit for vowels (Posner & Mitchell, 1967), and the identification of a letter as a vowel or consonant therefore requires the elicitation of the name code for that letter. As Posner (1970) pointed out, the availability of an immediate code common to all letters or all digits, and the absence of such a code for vowels, reflects the manner in which these materials are learned. With very prolonged practice, a common recognition unit can apparently be formed even for totally arbitrary collections (Rabbitt, 1967).

The very slow process in which recognition units evolve has been described in an important text by Gibson (1969). In a recent treatment of attention, Broadbent (1971) spoke of a slow process of *categorizing*, by which different stimulus configurations which are associated with the same response (e.g., the letter "a" in different handwritings) eventually come to elicit the same *category state* (here called perceptual interpretation). This type of perceptual learning results in a recognition system which is both highly refined and well adapted to the requirements of the environment.

ELEMENTARY CONCEPTS OF SIGNAL-DETECTION THEORY

According to the model introduced earlier in this chapter, the activation of a recognition unit depends on the match between sensory data and the specific features to which the unit responds, and on a variable that was labeled perceptual readiness. At any one time we are more ready to recognize some events than others, and a sensory signal that will enable us to recognize a familiar event with confidence may not suffice to identify a less familiar event. Bruner (1957) has offered a classic treatment of this perceptual readiness. He described the main manifestations of readiness by the example of a man who is peculiarly ready to see apples: "The apples will be more easily and swiftly recognized, a wider range of things will be identified or misidentified as apples, and in consequence the correct or best fitting identity of these other inputs will be masked [Bruner, 1957, p. 130]." The main determinants of the perceptual readiness for a particular stimulus are the past frequency of its occurrence, its probability of occurrence in the momentary context, and its present significance to the individual.

Recent treatments of perceptual readiness have increasingly used the tools and concepts of signal-detection theory. Some of the same concepts have also become central to theoretical treatments of attention (Broadbent, 1971; Norman, 1968; Treisman & Geffen, 1967). It will therefore be useful to briefly introduce some essential terms of signal-detection theory (for a more detailed, highly readable treatment, see Coombs, Dawes & Tversky, 1971).

Signal detection theory was originally developed to account for studies of detection and discrimination with a yes-no response (Green & Swets, 1966; Tanner & Swets, 1954), in the general paradigm illustrated in Table 5-2. In this paradigm the experimenter presents the target stimulus on some trials but not on others, and the observer indicates on each trial whether he believes the target was present or absent. The four entries in Table 5-2 represent the possible outcomes of such a trial.

The most obvious observation in this situation is the variability of the subject's behavior on repeated occurrences of the same condition. He sometimes says "Yes" and sometimes says "No" both when the stimulus has occurred and when it has not. Signal detection theory explains this unreliability by assuming the existence of internal noise, which causes the value of a hypothetical *sensory magnitude* to vary randomly over time, even in the absence of a signal. When a signal is shown, the sensory magnitude increases by a certain amount, depending on the intensity of the signal. If the signal is weak, it is possible that the sensory magnitude produced by the combination of signal and noise is less than

TABLE 5-2
The basic structure of the signal-detection paradigm.

		Response	
		No	*Yes*
Stimulus	Present	Miss	Hit
	Absent	Correct Rejection	False Alarm

values that occasionally occur by noise alone. The subject, of course, cannot know whether the sensory magnitude that he experiences on a given trial is due to noise alone or to a combination of noise and signal. What he does know is that higher values of sensory magnitude are more likely to occur when the signal was presented than when it was not. Under these circumstances, a rational observer will adopt a *criterion*, i.e., determine in advance a critical value of sensory magnitude. On any trial he will say "Yes" if the sensory magnitude exceeds that criterion, and "No" otherwise. The value of the criterion is often labeled by the Greek letter Beta.

Figure 5-5 illustrates these concepts by two elementary examples. In both panels A and B, the distribution at the left represents the probability that a value of sensory magnitude will arise from the internal noise of the system. The distribution of noise is assumed to be normal, and it has been standardized so that its mean is zero and its standard deviation is one. The two panels also present the hypothetical distributions of sensory magnitude for trials on which the signal is shown. The illustrations refer to the simplest possible situation, where the variance of the distribution is not affected by the introduction of a signal. The same considerations apply to the more realistic models, which assume that the signal causes both a shift of the distribution to the right and an increased variance. The signal in panel A is weak, and it causes the distribution of values to shift by only half a standard deviation, relative to the noise distribution. The distance between the two distributions, in standard units, is the *sensitivity* parameter of the theory. Sensitivity is commonly denoted by the symbol d'; in panel A, $d' = 0.5$. In both panels A and B, two values of the criterion are indicated, at values of 0.0 and 2.0 on the scale of sensory magnitude. A subject who adopts a criterion of 0.0 will say "Yes" if the value of sensory magnitude exceeds the mean of the noise distribution. A Beta of 2.0 signifies that the observer says "Yes" only if sensory magnitude is higher than the mean of the noise distribution by two standard deviations or more.

The four panels of Table 5-3 present the expected performance of an observer in the four situations illustrated in Figure 5-5 ($d' = 0.5$ and

TABLE 5-3
Distribution of responses in four signal-detection problems.

		$d' = 0.5$ *Beta* = 0.0		$d' = 0.5$ *Beta* = 2.0		$d' = 1.5$ *Beta* = 0.0		$d' = 1.5$ *Beta* = 2.0	
	Response	No	Yes	No	Yes	No	Yes	No	Yes
Stimulus	Present	.308	.692	.933	.067	.067	.933	.692	.308
	Absent	.500	.500	.976	.024	.500	.500	.976	.024

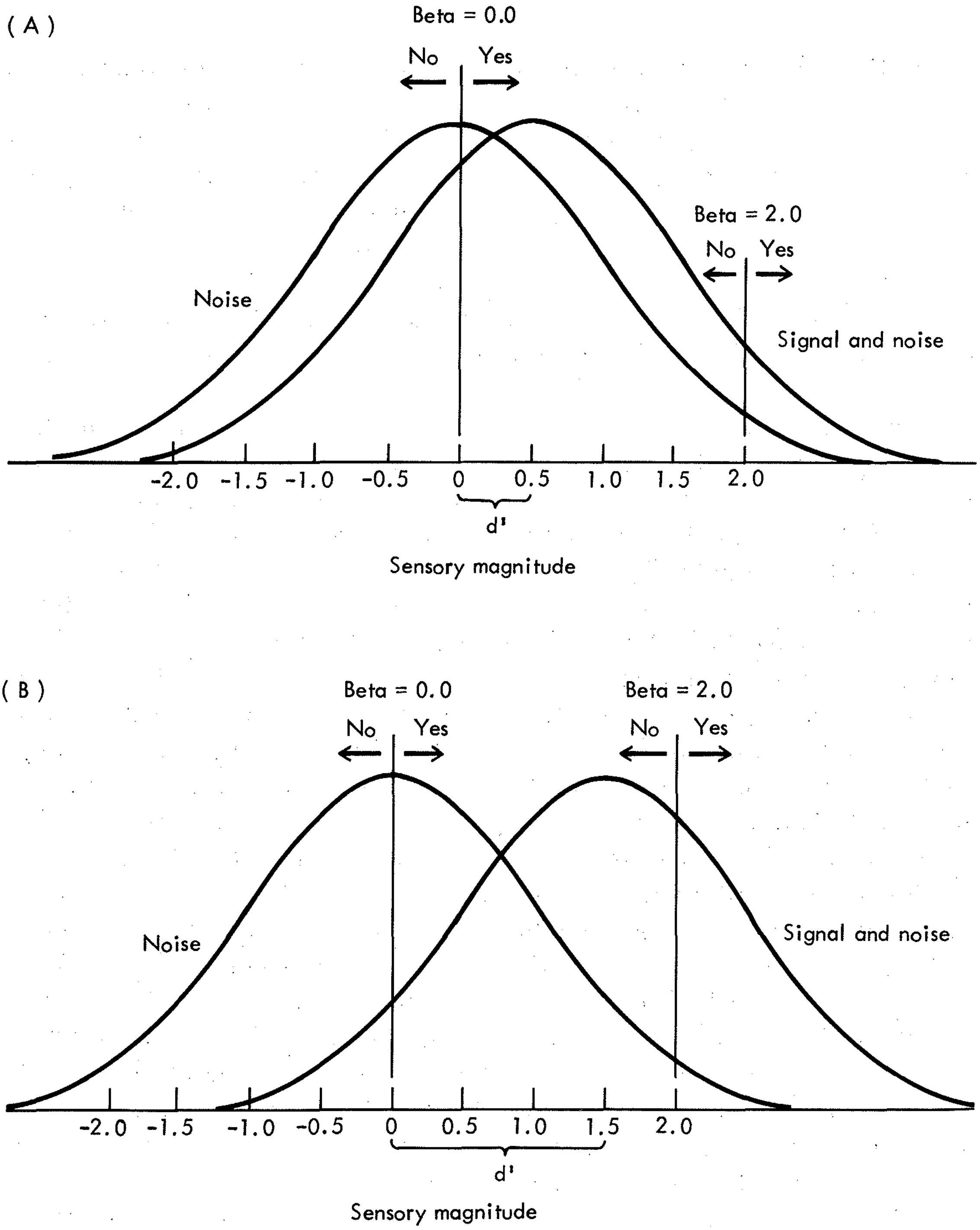

FIGURE 5-5
Constructions from signal-detection theory.

$d' = 1.5$; Beta = 0.0 and Beta = 2.0). Note that performance in the absence of a stimulus depends only on the criterion, while performance when the stimulus is present depends on both the criterion (Beta) and the discriminability of the signal (d').

In a real experiment, of course, the data are obtained in the form illustrated by Table 5-3, and the structure illustrated in Figure 5-5 is inferred from these data. Given the four entries in a table of experimental results, d' and Beta can be calculated, by using the assumptions of the model: i.e., normality of the distributions, and equality of the variances of the noise and signal-and-noise distributions. Furthermore, these assumptions can be checked and altered if needed, by measuring detection performance for the same signal (i.e., at a constant value of *d′*) under several values of the criterion. The criterion is most simply manipulated by instructing the observer to indicate his confidence in each response: any observer spontaneously adopts a lower criterion for the response "Perhaps there was a signal" than for the response "There certainly was a signal." Accordingly the ratio of hits to false alarms is expected to be higher when the subject expresses high confidence than when confidence is low. The theory provides a precise prediction of this ratio. The criterion can also be altered by other experimental manipulations. For example, an observer normally adopts a lower criterion if signals are frequent than if they are rare, and he also adopts a lower criterion when penalized for misses than when penalized for false alarms. The detailed predictions that signal detection theory entails for the effects of these manipulations have often been spectacularly confirmed.

The two parameters of the theory, sensitivity and the criterion, provide a much needed tool in the analysis of many situations. For example, observers in a vigilance task fail more often to respond to signals at the end of a tedious session than at the beginning. It is natural to ask whether this vigilance decrement is due to an impaired ability to detect the signal (lower *d′*), or to an increasing unwillingness to respond to signals (higher Beta). Broadbent (1971) and Mackworth (1969, 1970) have provided detailed treatments of this issue. Similarly, when a subject attends to one message and fails to respond to another, it is possible to determine whether *d′* or Beta has been altered by the lack of attention to the rejected message (Broadbent & Gregory, 1963; Moray & O'Brien, 1967).

PERCEPTUAL READINESS AS A CRITERION BIAS

The distinction between sensitivity and criterion suggests an elegant approach to the fascinating and intractable question of perception vs. response. It is tempting to identify *d′* as a measure of perceptual efficiency and Beta as a measure of response readiness. Indeed, the ease with which Beta can be altered in the detection paradigm appears to support such an identification. In the context of recognition, however, a low value of Beta for a particular recognition response has genuine effects on perception, as shown in the following example.

Consider the picture of the room in panel A of Figure 5-6. All observers see it as a normal rectangular room, but in fact it is not, as shown

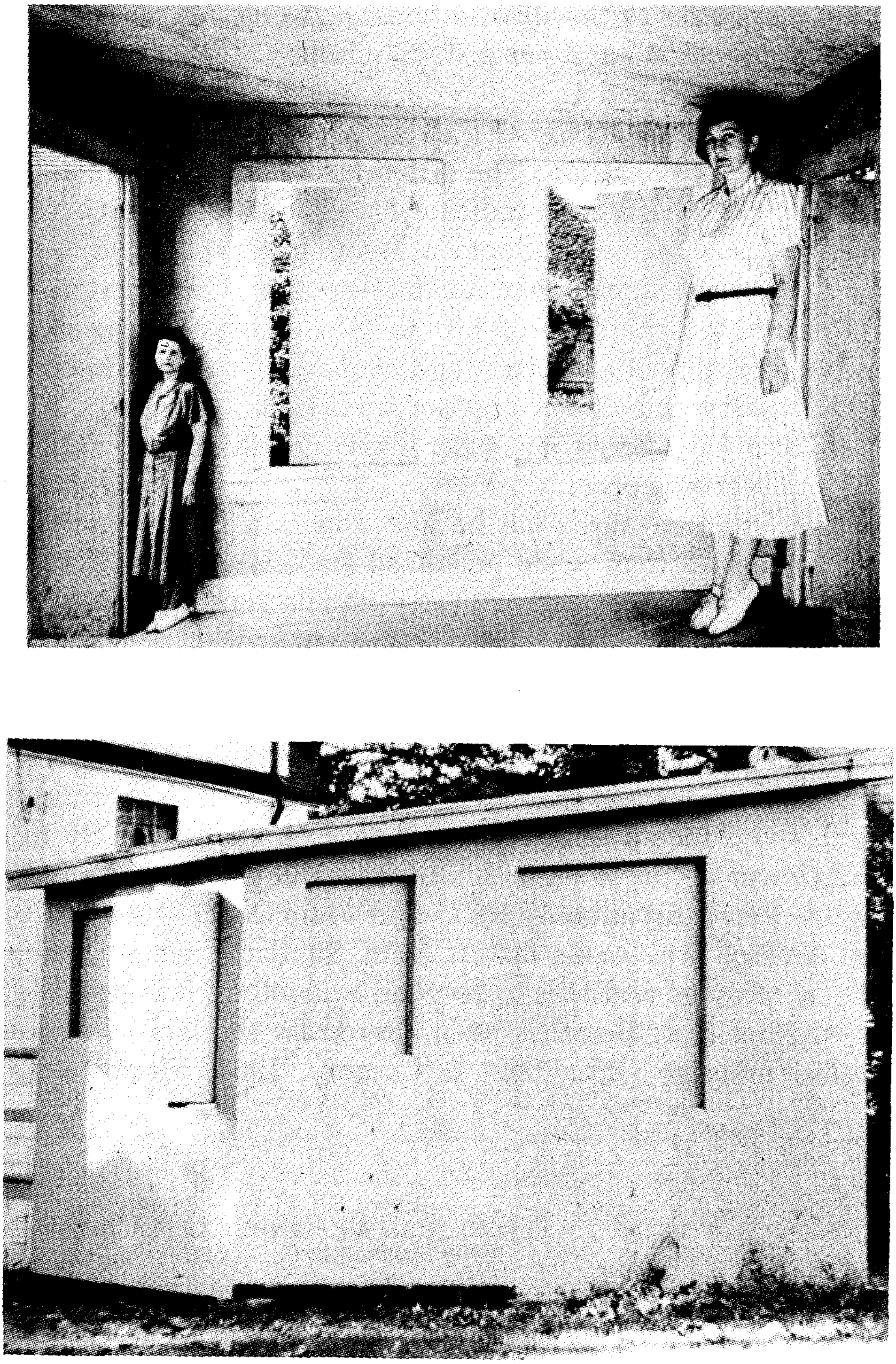

FIGURE 5-6
Interior and exterior views of a distorted room (Ittelson, 1952, with permission).

by the exterior view of panel B. The distorted room was carefully constructed so that when it is viewed or photographed from a particular spot, the image that it casts on the retina, or on the photographic plate, is identical to the image cast by a rectangular room (Ittelson & Kilpatrick, 1951). The photograph is ambiguous, because it provides no clue to distinguish the veridical distorted room from a standard room, or from an unlimited number of other distorted rooms that could be constructed to cast the same image. The ambiguity is not reflected in perception, which adopts an unequivocal decision in favor of the standard room. Now consider this example in the terms of signal-detection theory: the room was constructed to provide no signal that would be relevant to the decision, so that $d' = 0$. Thus, the perceptual decision that the room is rectangular rather than distorted is made in the absence of a relevant signal. As Table 5-3 showed, decisions made in the absence of a signal provide a pure measure of criterion bias. It follows that our seeing the rectangular room represents a criterion bias. The reader is therefore in a position to observe the powerful effects that such a bias can have in perception. Bruner's term of *perceptual readiness* is justly applied to such effects.

The well-known word-frequency effect is a controversial instance of perceptual readiness. The identification thresholds of frequent words are markedly lower than those of words which are rare in the language (Howes & Solomon, 1951). Frequent words are identified at a lower loudness than rare words in auditory presentation and at a shorter duration of exposure in visual tachistoscopic presentation. The elementary concepts of signal-detection theory cannot be applied to this situation, because the response vocabulary consists of the entire language in word identification, and only of two responses in the detection tasks that were initially treated in the theory. However, signal-detection theory can be adapted to the identification situation. Broadbent (1967, 1971) and Morton (1968, 1969a) carried out this task, and they derived testable consequences from several possible models of the word-frequency effect. The details of the mathematical analysis exceed the scope of the present review, but the flavor of the approach is conveyed by an illustration that Broadbent (1967) provided, of ". . . a vast array of test tubes, each partly full of water and each corresponding to a word in the language. The choice of one tube corresponds to perception of a word, and the probability of choice in any tube is greater when the water level in it is higher [p. 3]." In this model, the presentation of a word causes the level of water to rise in the appropriate tube. The amount by which the level rises corresponds to the sensitivity parameter of detection theory, and the initial level of water in each tube represents the level of the criterion for the recognition of "its" word.

In the terms of this analogy, Broadbent (1967) and Morton (1968) concluded that the presentation of a word does *not* raise the water level by a greater amount if the word is of high frequency than if it is rare. The word-frequency effect is entirely due to the initial level of water in the tubes, i.e., to a criterion difference. The main reason for this conclusion is that subjects' incorrect responses in the word-recognition task include large numbers of frequent words (Broadbent, 1967; Brown & Rubenstein, 1961; Pollack, Rubenstein & Decker, 1960). In the absence of stimulus information the subject is more likely to guess that a high-frequency word has been presented, which is clear evidence for a criterion bias. For a more detailed discussion of this conclusion, see Catlin (1969) and M. Treisman (1971).

Perceptual readiness probably mediates the context effects that play a crucial role in our ability to recognize events on the basis of impoverished and degraded cues. Thus, the recognition unit for "your" is almost certainly activated to some degree whenever we are exposed to the word "year." Nevertheless, mistakes of interpretation will be rare because of the probable presence of contextual cues which increase the readiness to recognize one of these words ("please give me y–r coat") or the other ("he will graduate next y–r").

In Figure 5-7, the concepts of signal-detection theory are related to the information-processing sequence which is the topic of this chapter. The figure suggests that the sensitivity (*d'*) and the criterion (Beta) for any response are each affected by events at several stages of the sequence.

Sensitivity (*d'*) is affected by the quality of the information that is delivered to the recognition units. Sensitivity is high if the initial signal was loud and clear. There is also evidence to suggest that sensitivity is high for an object to which we pay attention, and which has been selected at the earlier stage of figural emphasis (Broadbent & Gregory, 1963; Kahneman, Beatty & Pollack, 1967; Moray & O'Brien, 1967; Treisman & Geffen, 1967). In addition, sensitivity is affected by the availability of recognition units: if an American and a Chinese adult are compared in their ability to discriminate Chinese characters, the outcome will surely be a vast superiority of *d'* favoring the person who has had lifelong experience with these characters.

The criterion level (Beta) is determined by events at two different stages of the sequence. A state of perceptual readiness affects the selection of interpretations, in the manner illustrated by the example of the distorted room. In addition, a criterion bias may operate at the subsequent stage of response selection. A subject in a tachistoscopic experiment, having tentatively identified a briefly exposed word as WHORE may nevertheless opt for WHOLE as a safer response, lest his mind be thought dirty.

It is assumed in Figure 5-7 that the response system is itself noise-free. Both *d'* and Beta will be altered if there is unreliability in the selection or execution of responses. Imagine, for example, that the observer indicates a yes-no response by pressing one of two keys, which

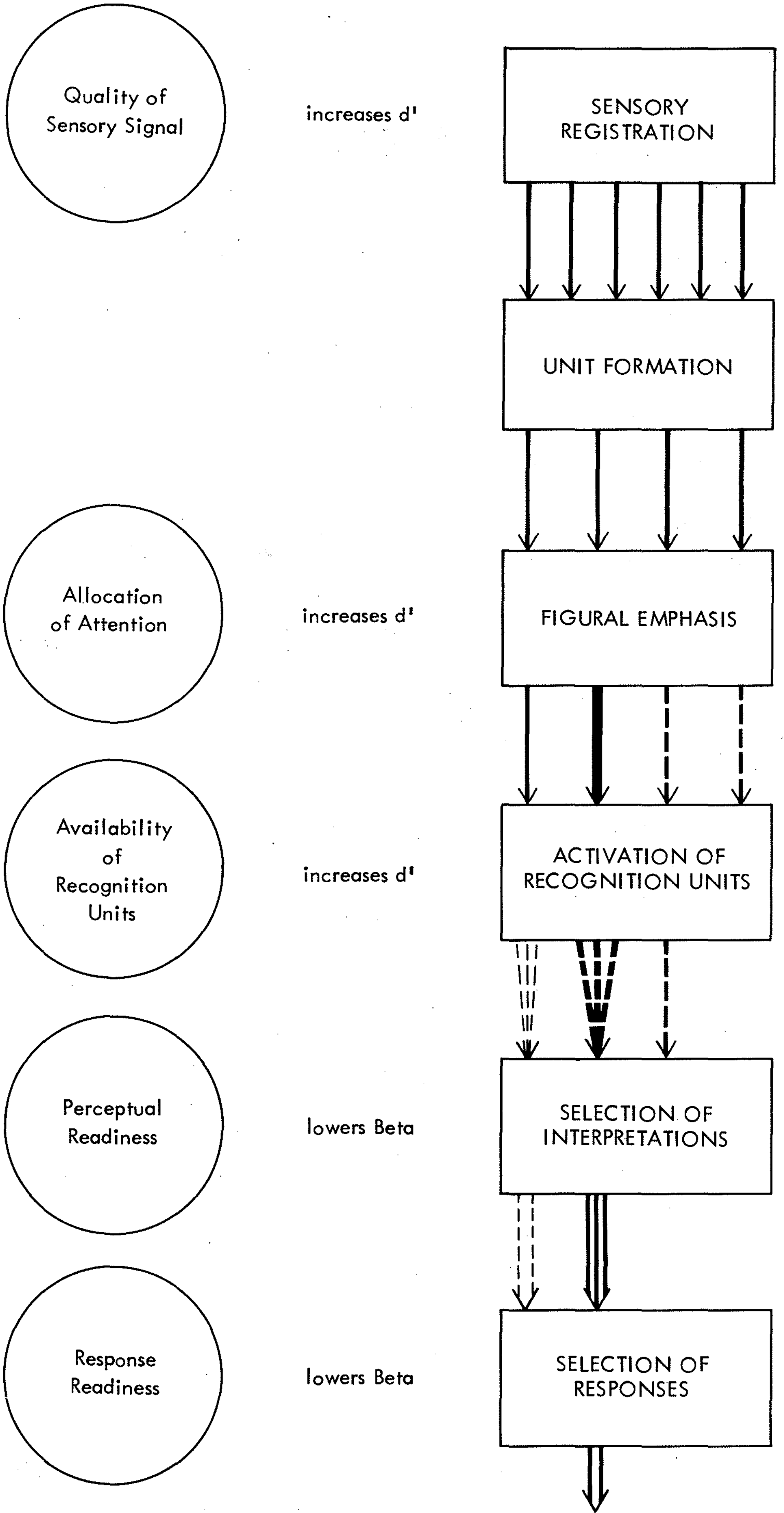

FIGURE 5-7
Determinants of sensitivity and criterion level.

are so close together that he presses the wrong key on a significant number of trials. Such response noise invariably lowers *d′*, and usually alters Beta as well. It is probably safe to ignore the effects of response noise in most psychophysical experiments. When signal-detection methods are applied to studies of attention, however, the possible occurrence of careless responses should not be neglected.

Two of the five processes mentioned in Figure 5-7 are neither new nor controversial: the quality of sensory registration surely affects *d′* while response readiness is reflected in the value of Beta. The three remaining processes deserve a final comment.

The model of Figure 5-7 assumes that the allocation of attention to an object enchances the sensitivity of the system (*d′*) in dealing with that object. This view is similar to the treatment of focal attention by Neisser (1967). Other authors have adopted the position that the withdrawal of attention from a stimulus causes a lowering of sensitivity, equivalent to an attenuation of the input (Broadbent, 1971; Broadbent & Gregory, 1963; Treisman, 1960; Treisman & Geffen, 1967). But Norman (1968) has proposed that all effects of selective attention can be explained by rapid alterations of criterion biases. We shall be concerned with this issue in Chapters 7 and 8.

The idea that the availability of recognition units is an important determinant of sensitivity was emphasized by Broadbent (1971). In the absence of appropriate recognition units, the selection of an appropriate interpretation becomes impossible.

Broadbent's term for perceptual readiness is pigeonholing, which he defines as "the process by which the nervous system adjusts so as to allocate larger or smaller numbers of states of evidence to each category state [p. xi]." In his terms, for example, the category state "rectangular room" is a pigeonhole to which states of evidence (corresponding to stimulus events, except for the effects of "noise" in the nervous system) are very liberally assigned. Pigeonholing is reflected in the setting of the criterion for a particular recognition. Pigeonholing, or perceptual readiness can affect the experience of perception. By suitable analyses, however, it is possible to distinguish between perceptual changes which represent a shift of criteria and other perceptual changes which represent alterations of the sensitivity of perceptual analysis.

REVIEW

This chapter has described some perceptual processes which must be considered in an analysis of attention. Perception was described as the achievement of a set of interpretations. These interpretations are attached to perceived objects or events which are segregated at an early stage of Unit Formation. The allocation of attention to some of these objects in preference to others at the stage of Figural Emphasis alters the quality of the information which is delivered to subsequent stages. Figural emphasis represents an allocation of attention, which is guided by the same enduring dispositions and momentary intentions that also guide the allocation of eye movements. A perceived object may attract attention because of a prior setting of figural selection. Alternatively, a recursive alteration of the allocation policy may follow either a tentative recognition that the object is significant—or a failure to establish an adequate interpretation of the object.

Recognition units are organized by sensory dimensions, and also by level of analysis. Units at several levels can collaborate in achieving an interpretation at one specified level: for example, the activation of a recognition unit for a word may facilitate the recognition of a letter in that word. In the terms of signal-detection theory, the availability of recognition units increases the sensitivity of the system (d'). The allocation of attention to an object was also assumed to affect d'. The criterion parameter of the theory (Beta) is determined by two types of readiness: perceptual readiness, which affects the selection of interpretations in subjective perceptual experience; and response readiness, which affects the selection of responses at a post-perceptual stage.

6

Attention to Attributes

In everyday communication we often use expressions such as "look at the shape of this vase," or "look at the color of that shirt," which direct the observer to attend to a particular attribute. The present chapter is concerned with the processes that permit us to obey such instructions. The first section reviews a few results from the vast literature of discrimination learning. Subsequent sections discuss the verbal report of attributes, speeded tasks of classification, and the Stroop test.

DISCRIMINATION LEARNING

The relation between attention and discrimination learning, originally stated by Lashley (1942; Lashley & Wade, 1946), was rediscovered and enthusiastically studied in the 1960s (e.g., Fellows, 1968; Lovejoy, 1968; Sutherland & Mackintosh, 1971; Trabasso & Bower, 1968). In a typical discrimination problem the human or animal subject is faced with stimuli that differ in many attributes, such as shape, color, size, and number. The subject must learn to respond to a particular class of stimuli, defined by a simple rule which he must discover, e.g., "all large objects are positive." In this example the size attribute or dimension is relevant, and all other attributes can be ignored. There is much evidence that learning in this situation occurs in two stages:

(*a*) The subject first learns to "attend" to the relevant dimension.
(*b*) He then attaches the positive response to the appropriate value of the relevant dimension.

Dramatic examples of discontinuity between these two successive stages of learning were described by Zeaman and House (1963), who studied discrimination learning in retarded subjects. Their data indicate that performance on a discrimination problem may remain at chance level over several hundred trials. Once learning starts, however, criterion is reached fairly quickly. The duration of the initial stage depends on the salience of the relevant dimension and on the intelligence of the subject. Zeaman and House observed that the relevant dimension was discovered sooner by subjects of higher mental age. Once in stage (b), however, retarded and normal subjects learned at about the same rate (see Fig. 6-1).

Early versions of a discontinuity theory of discrimination learning were stated by Krechevsky (1932, 1938) in terms of hypotheses and by Lashley (1942; Lashley & Wade, 1946) in terms of attention. The major assumption of discontinuity theories was that attention to a stimulus dimension is on an all-or-none basis: the subject either attends to the relevant dimension or he does not, and his performance on the discrimination task must remain at chance level as long as he attends to irrelevant dimensions. In the terms that Sutherland (1959) introduced, the relevant *analyzer* must be "switched on" and irrelevant analyzers must be switched off before learning can occur.

A modified discontinuity theory (Mackintosh, 1965; Sutherland, 1964) argues more moderately that some dimensions are vastly more salient than others, and that the most salient dimension tends to dominate performance. This modification of the original discontinuity theory is necessary to explain the fact that animals do learn something about the relevant dimension even while their performance is dominated by another, irrelevant dimension (Mackintosh, 1965). The modified theory retains the essential idea that the organism in a discrimination situation does not associate a response to the physical stimulus but rather, in Lawrence's (1963) phrase, to a stimulus-as-coded (S-A-C). Learning to produce the appropriate code, or to attend to the relevant dimension, is distinguished from learning the overt response.

Several formal models of learning (Lovejoy, 1966, 1968; Sutherland, 1964; Shepp, Kernler & Anderson, 1972; Trabasso & Bower, 1968; Zea-

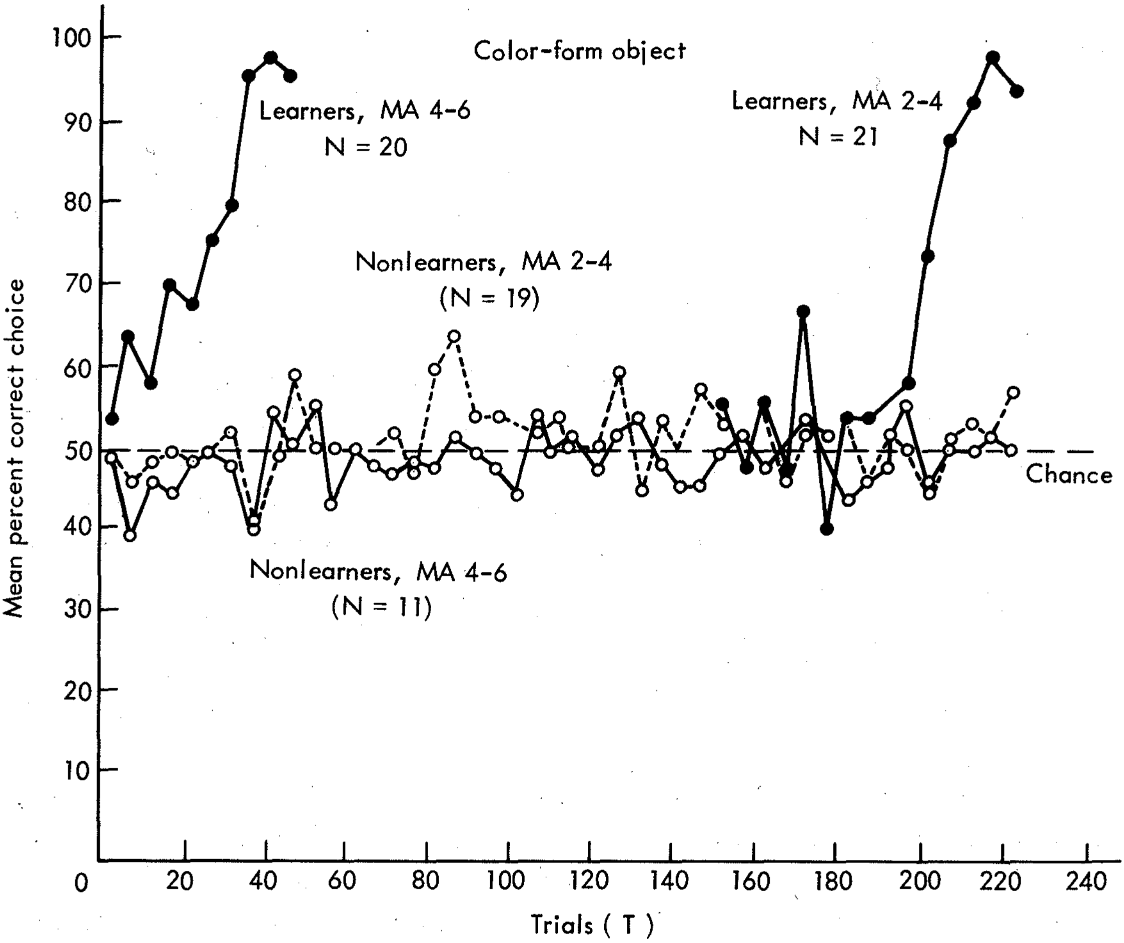

FIGURE 6-1
Effects of intelligence on discrimination learning are shown in the average performance of four groups classified by mental age and achievement. From *Handbook of Mental Deficiency,* edited by N. R. Ellis. Copyright © 1963 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.

man & House, 1963) incorporate a two-stage notion. These models have much in common, although they differ in important details, such as the number of dimensions that can be attended on each trial, and the precise effects of nonreinforcement on attention and on the overt response. All attention models can account for either continuity or discontinuity in learning. Continuous learning is typically observed when the relevant dimension is very obvious, so that the subject may be in stage (b) from the very first trial. On the other hand, sharply discontinuous learning is predicted if the relevant dimension is obscure or if the learner is very slow (see Fig. 6-1). Formal theories of discrimination learning are concerned with the details of several effects that Sutherland (1964) related to his two-stage model: the transfer of discrimination training along a dimension (Sutherland, Mackintosh & Mackintosh, 1965); the reversal shift effect (Kendler & Kendler, 1962, 1970a, 1970b); and the overtraining reversal effect (Lovejoy, 1966, 1968; Mackintosh, 1964, 1965; Wolford & Bower, 1969).

All attentional theories of discrimination learning assume that the various attributes of objects are not equally attended. In the simplest version of such a theory, only one dimension is attended when the discrimination is learned. For example, a pigeon may be selectively reinforced for pecking at a green circle, rather than at a red triangle (Jones, 1954). Shape and color are both relevant to this discrimination, and it is of interest to discover what the animal learned. Does it now peck at circles, or at green objects, or at both? The answer is obtained by studying transfer to a situation in which one of the relevant cues is kept constant while the other is varied. There is general agreement that individual subjects in animal experiments typically learn only one of the relevant cues and respond well to that cue and poorly to all others. The selected cue, however, may be different for different subjects or classes of subjects (Jones, 1954; Reynolds, 1961; Sutherland & Holgate, 1966; Sutherland & Mackintosh, 1964).

The dominance of a single cue in a complex of relevant cues is not restricted to lower animals. Trabasso and Bower (1968) illustrated various manifestations of cue dominance in a series of experiments with student subjects. Thus, subjects who have solved the problem on one cue often fail to notice any change when an initially irrelevant cue is made relevant (and redundant) in a later stage of the experiment. The results of transfer tests are usually consistent with a dominance hypothesis, although some subjects do solve discrimination problems on several cues. Trabasso and Bower (1968) found no consistent differences in learning rate between those subjects who solved a problem by two cues, and those who solved it by only one.

Some factors that make a particular cue more salient than others have been identified. Discriminability is such a factor. For example, if ellipses are presented which vary greatly in overall size and only slightly in eccentricity, and both size and shape are relevant, then size rather than shape will dominate behavior in a concept-identification task (Archer, 1962; Imai & Garner, 1965; Trabasso, 1963). The corresponding effect in animal learning is called overshadowing (Mackintosh, 1971).

Prior learning is also important. A dimension that has been successfully attended in one discrimination problem tends to dominate performance in subsequent discrimination learning (Lawrence, 1949, 1950). On the other hand, there is evidence that prior experience in which a cue is irrelevant significantly retards learning when that cue is eventually made relevant (Goodwin & Lawrence, 1955; Levine, 1962; Lovejoy, 1968; Mackintosh, 1964; Trabasso & Bower, 1968).

In addition, there are consistent individual differences (Shepard,

1964) as well as significant developmental changes in the relative salience of cues. The prevalence of mirror writing in children and its stubborn resistance to training indicate that orientation is not a very salient dimension at an early age (Fellows, 1968). Suchman and Trabasso (1966a, 1966b) studied the relative salience of the dimensions of color and shape for children of different ages. They used two experimental situations: judgments of similarity and discrimination learning. Similarity judgments were dominated by similarity of color at age three and a half; at age six, similarity of shape prevailed (Suchman & Trabasso, 1966a). This transition from color to form dominance is an important aspect of general cognitive development (Kagan & Lemkin, 1961). The dimension that dominates the similarity judgments of a particular child also determines his performance in discrimination learning (Suchman & Trabasso, 1966b). When both form and color are relevant, a child usually learns only one cue, and in most cases this is the same cue that also dominates his similarity judgments.

A significant theoretical question concerns the locus of the determinants of discrimination learning in the sequence of stages of information-processing. The question was foreshadowed by Krechevsky's usage of "hypothesis" for the same concept that Lashley later labeled attention. "Attention" suggests an effect on perception while "hypothesis" does not. Sutherland's concept of analyzer also implied an operation at an early stage of perceptual processing, and Treisman (1969) adopted that term in proposing a general approach to attention. When the subjects are rats, these distinctions have little operational significance, but the situation may be different with human subjects.

The general similarity of the results of human adults and lower animals suggests that Krechevsky's term "hypothesis" may have been more appropriate than "attention." If discrimination behavior reflects the activity of analyzers, then the appearance of the objects of discrimination would be expected to change in the course of learning. If subjective reports can be accepted as evidence, this is simply not the case: the perceptual world of a college student hardly changes when he discovers that color, rather than shape, is the relevant dimension in a concept-formation task. What the human subject learns is to attach the control of responses to one or the other of a set of unchanging perceptual interpretations. The term *code* is often used in this context. It is the coding of stimuli that is altered in most discrimination learning. The frequent finding that a single cue is learned when many are available suggests the important conclusion that subjects tend to develop the simplest possible codes that will suffice for the task at hand.

Discrimination training probably alters perceptual interpretations only when the relevant dimension must be discovered for the first time. Evidence cited by Gibson (1969) suggests that the intensive experience of first graders with the cues relevant to reading may have generalized effects on the perception of objects and on the ease with which they can be discriminated from one another. The slow process by which recognition units develop has been labeled *categorizing* (Broadbent, 1971).

SELECTIVE REPORT OF ATTRIBUTES

The process that Treisman called selection of an analyzer has been studied in an experimental situation originally introduced by Külpe in 1904. In this experiment, the subject is instructed to attend to a particular attribute of a briefly presented object, such as its shape or color. The subject reports the designated attribute on every trial, but he is also occasionally required to report some other features of the object. Observers in such experiments often make errors when reporting attributes to which they did not attend at the time of presentation, and introspection suggests that the character of the perceptual experience may be altered by the instruction to attend to a specific stimulus dimension. It is easy to convince oneself that listening to the loudness of a varying tone can provide a different experience than listening to its pitch. Introspection is a poor source of evidence, however, and Külpe's task obviously confounds perceptual and response variables. Wilcocks (1925) raised the question of whether Külpe's results represented an alteration of perception at the time of exposure, or merely a failure to recall the neglected attributes.

The controversy over Külpe's effect has been well reviewed by Haber (1966) and Egeth (1967), and a detailed description is unnecessary here. Briefly, there are three main explanations for the superiority of attended over neglected attributes:

(*1*) According to the perceptual tuning hypothesis, the selected dimension "stands out" in perception at the time of presentation.

(2) According to the response hypothesis, the attended attribute suffers less forgetting, because it is rehearsed more effectively and is reported first (Lawrence & La Berge, 1956).

(3) According to the encoding hypothesis, the attended and unattended attributes are treated differentially only at the point of transition from sensory memory to the verbally encoded representation of the stimulus (Haber, 1964a, b; 1966; Harris & Haber, 1963). The attended attribute is likely to be encoded first, thus gaining the advantage of primacy in recall.

Haber (1964b) also suggested that there may be no opportunity to encode some of the attributes of a briefly presented object: encoding the relevant attributes takes time, and the sensory memory decays very rapidly (Averbach & Sperling, 1961). By the time the first attribute has been encoded, information concerning other attributes may be lost.

The evidence for the encoding hypothesis was derived from an experimental situation initially introduced by Lawrence and La Berge (1956). On each trial the subject is shown two cards from the Wisconsin Card Sorting Task. The stimuli on each card can be described by the three attributes of numerosity, color, and shape (e.g., two red circles). The subject reports all the information of the display (three attributes for each of two objects), but he is sometimes instructed that one of the attributes is more important than the others (emphasis instruction). Lawrence and La Berge (1956) had noted that the emphasized attribute is usually the first to be reported, and they believed that the order of report accounts for the effect of emphasis on accuracy.

Harris and Haber (1963) introduced the hypothesis that the order of covert encoding may be more important than the order of the overt report in determining the emphasis effect. They instructed subjects to adopt one of two encoding strategies. *Object Coding* corresponds to the structure of English syntax. An example is: two red squares; three blue triangles. In *Dimension Coding* the information about the two cards is organized by dimensions, e.g., red, blue; square, triangle; two, three. The two strategies are often spontaneously adopted by uninstructed subjects. The crucial difference between them is that the sequence of dimension coding can readily be altered, whereas the sequence of object coding is fixed.

In the experiments, Harris and Haber (1963; Haber, 1964a) independently prescribed emphasis and order of report. They found that emphasis had an effect on accuracy even with order of report controlled. The most important result was that emphasis instructions altered the sequence of covert responses of subjects who were using a dimension code: they usually encoded the emphasized dimension first. Object coders could not do this. As a result, the effect of emphasis on the relative accuracy of report for the different dimensions was very pronounced for dimension coders, negligible for object coders.

On the whole, however, object coding was the more effective strategy. Object coders are faster (Haber, 1964b) and generally more accurate. This is an important result, which reflects a tendency to encode experience in terms of objects rather than in terms of dimensions. This tendency has other manifestations; in another experimental situation Lappin (1967) found that observers are much more accurate in reporting three attributes of a single object than in reporting one attribute for three objects. He also noted that order of report has a pronounced effect on accuracy in the latter case. Lappin (1967) concluded that the processing of a single dimension with multiple objects is necessarily serial at some stage, while the processing of several dimensions of a single object may be parallel.

Treisman (1969) accepted Lappin's conjecture. She explained his findings and other results by assuming the existence of a set of analyzers. Processing is necessarily serial within each analyzer, but it may occur in parallel in different analyzers. Since the various dimensions of an object are processed by different analyzers, they can be processed in parallel. To explain why parallel processing is impossible with one dimension and several objects, Treisman apparently assumed that there is only one analyzer of each kind. This is certainly incorrect: we are obviously capable of seeing more than one color at a time.

The model that was developed in the preceding chapter suggests a different interpretation. The process of figural selection allocates attention to objects rather than to dimensions. Analyses of all features of an object are facilitated when that object is figural. When the observer is required to report on attributes of three objects he must either extend the figural area at some cost in detail, or else deal with the objects in sequence.

In summary, the study of Külpe's effect did not provide compelling evidence that attention to a dimension alters perception. The intention to pay attention to a particular attribute appears to have its effects by increasing *response readiness* for a category of responses (e.g., color names), and by controlling the quality and the sequence of encoding and the order of report. This interpretation does not violate naive introspection, as you can probably confirm for yourself. Listen to a brief tune, while trying to pay special attention to the attribute of loudness. Now listen to a tune and attend to pitch and melody. How did you interpret the instruction to attend to one or the other attribute? You may find that you acted as if you were preparing to recall the designated attribute with special accuracy, after the termination of the tune. If this was the case, did you adopt different strategies to store the two attributes? Could the different experiences of listening to loudness and to pitch arise from different modes of rehearsal? The encoding hypothesis is compatible with such an account of the phenomenology of Külpe's task.

Speeded Classification

Attention to attributes has been extensively studied in reaction-time and speeded-classification tasks (Egeth, 1967). In a typical speeded-classification experiment the subject is given a deck of cards, each containing a design; he is to sort the cards into piles according to some attribute (e.g., all red objects into one pile, all blue objects into another). As in the case of discrimination learning, the other attributes of the design may be correlated with the designated relevant attribute (e.g., all the red objects may be small circles printed near the top right corner of the card, while all the blue objects are large triangles printed near the bottom left corner). Alternatively, the other attributes may be orthogonal to the relevant dimension (e.g., the red objects that are to be sorted together may vary in shape, size, vertical and horizontal position).

The basic design can be modified in a variety of ways (Posner, 1964). The most elementary version, in which a single attribute is relevant, is called a *gating* task. The term "filtering" has sometimes been used in this context. In this book, however, filtering refers to the selection of inputs which share a particular attribute (e.g., all words printed in red ink in a page of text), but call for distinct responses (e.g., reading each word). In the gating variant of speeded classification, on the other hand, the same response is made to all the stimuli that share the criterial attribute.

The *condensation* task is a more complex variant of speeded classification. Here the stimuli requiring a single response are defined either by a disjunctive rule applicable to one dimension (e.g., red or blue stimuli vs. green or yellow), or by a rule involving several dimensions (e.g., red squares or blue circles vs. red circles or blue squares). Keele (1970) observed that the second variant of condensation is far more difficult than the first. Accordingly, Gottwald and Garner (1972) referred to the easier variant as *grouping*, and retained the term condensation for the harder task. The dependent variable in speeded-classification tasks is the speed achieved in sorting cards. Alternatively, the cards may be successively presented in the tachistoscope, and the subject may be required to indicate his response by pressing an appropriate key as quickly as possible.

A vast amount of research has been devoted to the questions of whether the attributes of a stimulus are interrogated sequentially or in parallel, and of whether this interrogation is exhaustive or self-terminating. The results of this research are confusing and contradictory (e.g., Biederman, 1972; Biederman & Checkosky, 1970; Garner, 1970; Rabbitt, 1971; Smith, 1968). This outcome should not be surprising. Some of the complex tasks that have been studied certainly involve covert verbal encoding of the various stimulus attributes prior to the selection of a response. In such tasks the processing of the relevant dimensions will appear to be serial, because the encoding is serial. Furthermore, verbal encoding is relatively flexible. The order of encoding can be altered, as was shown in the preceding section, and the subject may be able to terminate the encoding as soon as he accumulates sufficient information (e.g., Biederman, 1972). In other situations the subject's task is simpler, and he soon learns to dispense with verbal encoding. In those situations, analyses of multi-attribute discrimination problems provide evidence of parallel processing (e.g., Biederman & Checkosky, 1970; Hawkins, 1969). Furthermore, the disappearance of verbal encoding is certainly gradual, and the prevalence of serial or parallel processing varies with practice (Marcel, 1970).

There is no reason to believe that subjects always process information in one manner, either serially or in parallel. As Garner (1970, p. 350) pointed out: "Why must the organism do one or the other? Very probably it can do either, depending on the task and the stimuli. And even as likely is that the organism frequently does both, not in the sense of doing first one and then the other, but in the sense of doing both simultaneously." In a comprehensive review of modern reaction-time research, Rabbitt (1971, p. 262) stated incisively: "My view is that the evidence leads to no conclusion, but rather to doubt about the value of trying to distinguish between serial and parallel processing as a guide to the development of models and to experiments."

A more fruitful question about speeded classification concerns the efficacy of gating. When the subject is told to sort stimuli according to one attribute—e.g., color—does he in fact ignore variations in other attributes? There are two ways of studying this problem: when another dimension is correlated with the relevant dimension (e.g., the red objects are always large and the blue objects are small), classification may be facilitated by a *redundancy gain.* When the two dimensions vary independently, there may be interference. If the subject strictly obeys the gating instruction, however, neither facilitation nor interference should occur.

The analysis of the perceptual sequence presented in the preceding chapter emphasized the importance of the initial processes of unit formation. From that analysis it is obvious that the hue and the size of a single object (or group) are much more likely to interact than are the hue of one object and the size of another. Similar considerations led Lockhead (1966a, b) to a distinction between integral and nonintegral dimensions. Integral dimensions are those which are presented simultaneously and at the same place. In short, they are the dimensions of a single object: "Phenomenologically, it is difficult for a normal person to look at a lighted and colored incandescent bulb without being aware—at one time—of its hue, brightness, size and form [Lockhead, 1966a, p. 103]." Garner (1970, p. 354), carefully avoiding phenomenology, offered a very similar definition: "Two dimensions are integral if in order for a level on one dimension to be realized, there must be a dimensional level specified for the other. For example, a visual stimulus must have a brightness and a hue and a saturation and a size and a form. That fact makes any pair of these dimensions integral."

Garner and Felfoldy (1970) conducted speeded-classification experiments to study the effects of integrality. When two integral dimensions were perfectly correlated in a deck of cards, and the subject sorted cards according to one of these dimensions, sorting was faster than in control situations in which the irrelevant dimension was not varied. This finding was obtained with the hue and brightness (chroma and value) of a color chip and with the horizontal and vertical position of a dot. Conversely, interference was observed when the irrelevant dimension in an integral pair was randomly varied. There was neither facilitation nor interference when the dimensions were assigned to distinct objects, except in the rather trivial case where the subject found it more convenient to concentrate on the "irrelevant" object, which provided a better clue than the relevant one (Felfoldy & Garner, 1971).

Garner (1970) related the effects of integrality in speeded classifications to some observations obtained in the scaling of similarity. Thus, Shepard (1964) had subjects judge the similarity of circles, each containing a single radius; the size of the circle and the orientation of the radius were varied. These two dimensions are not integral, because they refer to separable objects. As might be expected, subjects encounter severe difficulties in evaluating the similarity of such compound stimuli (Eisler & Knoppel, 1970). Which two objects are more similar: two circles of the same size with different radii? or two circles of different sizes with identically oriented radii? Shepard (1964) noted that some subjects' judgments were more affected by circle size, while others were more affected by the orientation of the line, and he attributed these differences to attention. More important, he concluded that the pattern of similarity judgments was intermediate between the pattern predicted by a "city-block" model (in which the "distance" between stimuli corresponds to the sum of distances on two dimensions) and a pattern predicted by a Euclidean model (in which distance is measured along the shortest path between two points). Hyman and Well (1968) performed a similar experiment with decidedly nonintegral attributes: the hue of one color chip and the brightness of another. Their similarity judgments conformed to a city-block model. Garner and Felfoldy (1970) used the stimuli of these two experiments in their study of speeded classification, and they found no interference between nonintegral dimensions. Thus, Garner (1970) concluded that integral dimensions have three characteristics:

(*1*) They lead to a Euclidean metric in direct distance scaling.
(2) When correlated in a classification task, they yield a redundancy gain.
(3) When varied orthogonally they cause interference in classification (Egeth & Pachella, 1969; Garner, 1969).

The last characteristic is not always found. Subjects can sometimes use the redundancy of integral dimensions when it is available, but also avoid interference when there is no redundancy (Felfoldy & Garner, 1971; Garner, 1970). However, the rules of integrality provide a useful first approximation. In general, these findings confirm the conclusion that the perceiver has little control over the initial stage of perceptual analysis, which determines the effective stimuli for subsequent stages. As Rabbitt (1971, p. 263) concluded: ". . . what is perceived as 'a stimulus' depends critically on the organization of the nervous system rather than on the arbitrary intuitions of experimenters who select and define component 'attributes' or 'dimensions' of display in terms of semantic convenience or ease of preparation of stimulus material."

RESPONSE CONFLICT: THE STROOP TEST

Man's ability to "switch off analyzers" or gate irrelevant attributes can be studied by attaching conflicting responses to several attributes of an object. In the test of selective efficiency, the subject is required to respond to one of these attributes, and to ignore the others. A perfect selection device would simply prevent the analysis of all irrelevant attributes, and thereby avoid response-conflict at the source, but man is not endowed with such a device. Thus, Egeth's (1967) review of filtering in speeded-classification tests concluded that subjects in such tasks can ignore irrelevant stimulus attributes (Morin, Forrin & Archer, 1961; Fitts & Biederman, 1965; Imai & Garner, 1965), but only when no conflicting responses have been attached to these attributes (Montague, 1965). When the competing responses are weak, interference may be slight or absent altogether (Well, 1971), but when the responses are overlearned, some interference always occurs.

Conflict between responses to different attributes of the same object has been extensively studied in an experimental situation devised by Stroop (1935) (see p. 32). The stimulus materials consist of three types of cards: On card W, the subject must read a set of color names; the relevant attribute here is letter shape. On card C, he must name the colors of a set of color patches. On card CW, he must name the colors in which a set of words are printed. The relevant attribute is color, but the words on card CW are themselves color names. Thus, the subject may see the word "red" printed in orange, and he must respond "orange." The most dramatic finding with this test is the difficulty of card CW. Jensen and Rohwer (1966) describe the behavioral effects of this card: subjects ". . . become more tense, they strain forward, they take on the expression of eyestrain, they gesture with arms and hands, and occasionally they stamp their feet. Exaggerated vocal emphasis is also characteristic. . . . Repeated testing decreases these overt signs of stress, though subjects never come to regard the CW task with the same bored equanimity that they finally show toward cards C and W [p. 59]." The relative difficulty of this task resists extended practice (Jensen, 1965). Subjects only improve by the adoption of such techniques as squinting or deaccommodation to make the words illegible.

Interference in card CW occurs even when the words whose colors are to be named are not themselves color names. Klein (1964) suggested that it is harder to say the colors of any nameable symbol than it is to say the colors of a set of asterisks, and that the amount of interference follows a gradient of color-relatedness. For example, color-related words such as "sky" or "lemon" tend to cause greater interference than nonsense syllables. Similarly, Morton (1969b) observed that it is difficult to sort cards by the numerosity of the symbols printed on them, if these symbols happen to be other digits. Fox, Shor, and Steinman (1971) replicated these results, and they also reported interference when direction names (Up, Down, Right, Left) appeared in incongruent positions.

Klein's conclusion that any nameable symbol will cause interference was not supported in several subsequent studies (Egeth, Blecker & Kamlet, 1969; Pritchatt, 1968; Keele, 1972). It seems that the interference effect occurs primarily when the printed word elicits a coding response which is relevant to the task. Thus, the interference in the Stroop test is a result of competition at the level of encoding: some responses are "primed" by the task, and the elicitation of these responses by an irrelevant stimulus causes interference. It follows from this analysis that facilitation could be produced if the responses to the relevant and irrelevant attributes are congruent. This was found to be true in a reaction-time experiment, where the subject had to name the color of a tachistoscopically presented color word (Hintzman *et al.*, 1972). There was interference when the word and the color were different, but facilitation when they were the same. Similar results were obtained by Morton (1969c) in a card-sorting task.

These results illustrate the concept of *Response Readiness.* Responses appear to be organized in sets. When a set of responses is relevant to the task (e.g., color names), these responses are readily elicited even by inappropriate stimuli. Facilitation arises if the responses elicited are compatible, and interference if the responses are competing.

In addition, the findings obtained in the Stroop paradigm strongly support the general conclusion of this chapter: subjects cannot prevent the perceptual analysis of irrelevant attributes of an attended object.

REVIEW

When an object is perceived, many perceptual interpretations are made, apparently in parallel. The various attributes of the perceived object correspond to these interpretations. There is little evidence that an intention to attend to a particular dimension of experience can prevent the perceptual interpretation of other dimensions. Attention to attributes affects the post-perceptual stage of *Response Selection* by increasing the readiness to produce codes of the relevant dimension (e.g., color words), and the tendency to attach overt responses to such codes.

Studies of discrimination learning indicate that responses are often attached to a single attribute even when several are relevant. The salience of the attributes and the prior learning history of the organism determine which of the attributes will control behavior. These observations, among others, have suggested models in which analyzer systems can be switched on or off, depending on circumstances. However, the fact that similar rules apply to concept learning with adult humans indicates that discrimination learning can occur without perceptual modification. Similarly, the results in Külpe's paradigm are explained satisfactorily as an effect of instructions on encoding. Studies in this paradigm have shown that object coding is common and generally efficient.

Studies of speeded classification have shown that certain pairs of attributes are integral. It is relatively difficult to ignore an irrelevant attribute which is integral with the relevant attributes. Attributes of separate objects are not integral, but attributes of a single object often are. Thus it is easy to ignore an irrelevant object but considerably harder to ignore irrelevant attributes of an attended object. Results in several variants of the Stroop test confirm the conclusion that irrelevant dimensions cannot be switched off at will. Responses associated with irrelevant attributes interfere most severely with performance if they belong to the same set as the relevant responses.

7

Focused Attention – Findings and Theories

Debate about the nature of selective attention has centered on tasks that require the subject to select inputs, or filter information. The classic example of input selection is the situation that Cherry (1957, p. 278) described as the cocktail-party problem: a guest at a cocktail party usually listens to one conversation and ignores all others, regardless of how loud they may be. In general, a person is said to select inputs when he focuses attention exclusively on stimuli that originate from a particular source or share some other characteristic feature.

Experimental studies of input selection have typically used auditory stimuli. Broadbent (1958) defended the choice of the auditory modality for the study of attention on the grounds that auditory attention can be studied without the encumbrance of the orientation movements which dominate visual attention. When a medley of auditory messages is fed through headphones, the listener must rely on central selective mechanisms to isolate the relevant message and ignore the others, whereas the selection of relevant visual stimuli is usually carried out by eye movements. To obtain a pure measure of central processes of visual selection, the experimenter is therefore compelled to present brief stimuli which are removed before eye movements can occur. This tachistoscopic situation is exceedingly contrived, and the auditory task with multiple messages is clearly more natural and ecologically representative. As this chapter will show, however, the emphasis on audition in the study of selective attention has limited the theoretical treatment of the problem in several ways.

The performance of a listener who selectively attends to a relevant message in the presence of an irrelevant message can be evaluated by two sets of questions: (1) How effective is the processing of the relevant message? Is comprehension impaired relative to a control situation in which that message is presented alone? (2) How effective is the rejection of the irrelevant message? In what ways, and at what stages, are the selected and rejected messages treated differently?

The first section of this chapter summarizes experimental findings in studies of focused attention. Subsequent sections review several theories that have been proposed to explain these findings.

EXPERIMENTAL STUDIES OF FOCUSED ATTENTION

Man's notable ability to resist distraction is a manifestation of selective attention. The success with which distraction can be resisted was documented in a series of early studies reviewed by Woodworth (1938). On the average, measures of intellectual functions were barely impaired by intense irrelevant stimulation. However, distraction is resisted at a cost: motor tension and autonomic manifestations of arousal are higher than normal. Thus, one is much more likely to break one's pencil while writing an examination in a noisy room than when the room is quiet. One is rarely justified, however, in attributing failure in a test to the presence of distracting conditions.

In the early studies of distraction, the subject's attention was focused on his mental activities, but modern studies of selection typically deal with the ability to select a relevant input in the presence of others. Many studies have used the shadowing task, in which the listener follows a message by repeating every word, and attempts to ignore other messages to which he is simultaneously exposed. Cherry (1953; Cherry & Taylor, 1954) established that the presence of a distracting message barely impairs shadowing performance when the rejected and attended messages are distinguished by an obvious physical characteristic, such as spatial origin. In some of these experiments Cherry used the method of dichotic presentation, in which two messages are presented by earphones to different ears. He observed that subjects are always aware of the presence of the rejected message on the unattended ear, but know virtually nothing about it when subsequently questioned, not even the language in which it was spoken. They also fail to detect a switch to inverted speech on the rejected channel. However, they are invariably aware of the sex of the voice on the rejected channel and easily detect any major physical change, such as a change of voice, a switch from voice to tone, or an isolated sound (Lawson, 1966; Treisman & Riley, 1969). Shadowing is most effective when both the relevant and the distracting stimuli are unambiguously labeled. Treisman (1964b) found marked interference when a subject shadowed one continuous message while simultaneously exposed to *two* distracting messages from different sources.

Spatial position is the most effective attribute for identifying the selected message. It is relatively easy to attend to a position, both with auditory stimuli (e.g., Poulton, 1953; Spieth, Curtis & Webster, 1954; Treisman, 1964b) and in tachistoscopic visual presentation (e.g., Sperling, 1960). In the case of audition, selection by location can be precluded by presenting several messages which originate from the same position. When several messages are presented in this manner, subjects are able to isolate the relevant message by its pitch or loudness, but only with great difficulty (Treisman, 1964b).

Selection of inputs can be almost perfectly effective when guided by an appropriate cue. This is true both in the shadowing situation and in other tasks. In tachistoscopic presentations of complex arrays, for example, the subject can be set to select items in a particular row (Sperling, 1960) or items of a particular color (von Wright, 1968, 1970), and he performs almost as well as if the irrelevant material had not been present. Monitoring an auditory message for critical items is almost as effective in the presence of a competing message to the other ear as without that message (Moray & O'Brien, 1967), and the covert rehearsal of a memorized list is barely affected by the presentation of loud rhythmic music (Kahneman, 1970).

Selection is effective only when the relevant and irrelevant inputs differ in obvious physical characteristics. In Broadbent's terms, selection by stimulus set is effective, selection by response set is not. Thus, the relevant items in a tachistoscopic presentation can easily be selected by spatial location, but it is essentially impossible to selectively attend to the digits in a brief exposure of a mixed array of digits and letters (Sperling, 1960). Similarly, it is exceedingly difficult to isolate an auditory message in English from a simultaneous message spoken by the same voice in French (Treisman, 1964a).

Recent studies of auditory attention have used tasks other than shadowing. In the monitoring task, the subject is exposed to a continuous message but responds only to occasional target items. Monitoring a list of letters for occasional digits is not seriously impaired by the presentation of an irrelevant message to the other ear (Moray & O'Brien, 1967; Underwood & Moray, 1972). Similarly, a subject instructed to press a key as soon as he hears an animal name in a recorded message responds as fast in the presence of an irrelevant message as when that message is absent (Ninio & Kahneman, 1973).

The main difference between shadowing and monitoring is that the former task requires continuous overt responses, while the latter does not. Several experiments in my laboratory have investigated a recognition task that requires no immediate response (Henik, 1972; Kahneman, 1970; Levy, 1971). Two messages, each consisting of 31 unrelated words, are presented dichotically and the subject subsequently attempts to recognize some of the words that were presented to the right ear. The recognition choices also include an equal number (eight) of words presented to the left ear, and of words that were not presented at all. The critical feature of the design is that the subject is penalized for recognizing words that were presented to his left ear.

Three experiments using a fast rate of presentation (two words/sec in each ear) compared recognition in focused attention and in a control condition where the relevant message was presented alone. The presentation of an irrelevant message caused a decrement in the recognition of relevant items (from 61 percent to 54 percent). The percentage of false recognitions of unpresented words was 32 percent in both conditions, and 37 percent of the left-ear words were judged to be familiar. Thus, selectivity was high, though far from perfect. Selectivity was only slightly poorer at a slower rate of presentation (one word pair/1.5 sec). Finally, subjects were able to prevent a high rate of intrusions even when the words were presented to the two ears in alternation at the comfortable rate of one word every .75 seconds. The results show that a listener could usually refrain from paying attention to the irrelevant items, even when no relevant word was presented at the same time. However, intrusions of left-ear items were more frequent in an experiment (Henik, 1972) where only a few such words were presented. It appears that the continuity of the irrelevant message is important in permitting that message to be ignored.

There is no doubt that selective attention was less effective in our recognition experiments than in studies of shadowing. In one of these studies subjects who shadowed a message on one ear later failed to recognize a phrase that had been repeatedly presented to the other ear (Moray, 1959). This result was obtained although the subjects were not specifically enjoined not to listen to the irrelevant ear. In our studies subjects were penalized for listening to the left ear but they nevertheless did so occasionally. The difference is due in part to the shadower's own voice, which functions as a source of interference (Underwood & Moray, 1972). In addition, limitations of capacity are probably involved. Shadowing is more demanding than monitoring, and it leaves less spare capacity to be captured by the irrelevant message.

An ingenious study by Zelnicker (1971) provides further evidence for the role of capacity demands in focused attention. Three groups of four auditory digits were presented in rapid succession (e.g., 3256-8129-6543). There were two experimental conditions, which may be labeled Easy and Hard. In the Easy condition the subject repeated the first group of digits twice (3256-3256), synchronizing his responses with the second and third groups heard on the tape. In the Hard condition he repeated the first group while hearing the second, and he repeated the second while hearing the third. The correct response in the example would be: 3256-8129. In that condition, it was necessary to say 3256 while listening to 8129, which was the set to be reported later.

In both conditions the subject was also exposed to a playback of his own voice, which was delayed by 0.2 seconds. Such delayed auditory feedback (DAF) often causes stuttering. The amount of stuttering was compared in the first group of digits that the subject reported (3256, in both conditions). There was less stuttering in the Hard condition. Attempting to listen to the second group of digits while speaking made it easier to ignore the DAF. Since DAF is an extremely unpleasant experience, the subjects must have been motivated to ignore it under both experimental conditions. It is consistent with a notion of limited capacity that they were more successful when engaged in a demanding task.

The evidence reviewed thus far is generally consistent with predictions from Broadbent's (1957a, 1958) filter theory. The theory assumes that a filter sorts simultaneous stimuli by obvious physical characteristics, such as position, voice quality, or color. Further perceptual analyses are applied only to stimuli which share the property that defines the relevant "channel" or message, e.g., words presented to the right ear or letters printed in blue. Other stimuli are rejected and filtered out. Irrelevant sensory information is stored momentarily as an "unanalyzed tape recording" (Treisman, 1969), but is permanently lost unless a shift of the filter retrieves it from sensory storage. Thus, the material presented to an irrelevant channel is not analyzed in perception, beyond a few tests on physical features. Specifically, filter theory implies that speech messages on an irrelevant channel are not analyzed as speech.

Strong evidence was advanced against filter theory soon after it was formulated. Thus, although the theory accounts for the cocktail-party phenomenon of selective attention, it fails to explain another common experience of cocktail parties: the detection of one's own name as soon as it is mentioned in an otherwise ignored conversation. Moray (1959) documented this everyday experience in the shadowing situation. He observed that subjects were much more likely to notice a message on the rejected ear if it was preceded by their own name than if it was not. Moray's results are incompatible with Broadbent's assumption that the sounds arriving at the rejected ear are not analyzed as speech.

Neisser (1969) developed a visual analogue to the auditory shadowing situation, and he obtained results very similar to Moray's. He required subjects to read coherent text aloud and to ignore words printed in red under each line of the selected text. Subjects can do this very well. The situation is similar to ordinary reading, where the lines just above and below the attended line do not intrude. Neisser also showed that subjects do not recognize the words presented on the ignored lines, even when the same word is repeated several times. Two-thirds of his subjects, however, noticed their own name on a rejected line.

There is much additional evidence that, even in the shadowing situation, the message on the rejected ear is analyzed as speech. Treisman (1960) occasionally switched messages from one ear to the other, usually at a point of high redundancy in the relevant shadowed message. On a substantial number of instances, subjects followed the attended message into the incorrect ear for one or two words before reverting to the designated ear. Such transitions were most likely to occur if the shadowed message was connected prose. Most of her subjects were unaware of their transition errors. Treisman's results demonstrate that continuity of meaning can briefly overcome the effect of channel selection in determining the subject's shadowing response. These findings are incompatible with Broadbent's early version of filter theory, because they show that the message to the neglected ear is not necessarily rejected at an early stage of processing.

Another experiment of Treisman's (1964c) demonstrates an important effect of selective attention and an important difficulty for filter theory. She studied a situation originally devised by Cherry (1953), in which identical messages, one lagging behind the other, are presented on the two ears. The subject is to shadow what he hears on one ear, and he is not told that the two messages are actually identical. The lag between the messages is gradually reduced until the subject comments on their identity. Treisman (1964c) repeated and extended these observations. She found that subjects recognize the identity of the two messages when the lag is about five seconds, but only if the relevant message leads. When the neglected message leads, identity is recognized only at an interval of one or two seconds. These results show that the trace of the shadowed message persists longer than that of the rejected message, just as filter theory would predict. Contrary to filter theory, however, the rejected message is apparently analyzed as speech: subjects realize the identity of messages even when they are spoken in different voices; and bilingual listeners often recognize the identity of a message and its translation. Neither result should occur if the rejected message is not analyzed as speech. At the very least, these findings show that some verbal analysis of the rejected message sometimes occurs.

There is additional support for this conclusion. Lewis (1970) recorded latencies for shadowing unrelated words and found that the shadowing latency for a word is significantly increased by simultaneously presenting its synonym to the other ear. Evidently both words must be recognized for this effect to occur. However, Treisman (unpublished) observed that this synonym effect occurs only at the beginning of the message. Selectivity improves within a few seconds and the content of the irrelevant message no longer affects shadowing latency. An intriguing result was reported by Corteen and Wood (1972). They first associated an electric shock to the presentation of city names in a word list. Later, city names which were included in the rejected message in a dichotic shadowing task often elicited a galvanic skin response, although they were never consciously identified and did not interfere with the shadowing performance.

Selectivity with auditory stimuli appears to be generally poor when the messages are brief. Thus, Brown (1970) instructed subjects to attend to one ear and then presented a single dichotic pair of words. Precuing the relevant ear did not improve the subject's ability to recognize a word presented on that ear. With somewhat longer messages, however, such precuing is very helpful (Broadbent, 1952; Spieth, Curtis & Webster, 1954). These results indicate that focusing attention takes time.

Greenwald (1970a, b) described another instance of a failure to filter a very brief message. He simultaneously presented a visual and an auditory digit and recorded subjects' reaction times for reading the visual digit. The subjects were unable to reject the irrelevant auditory digit; their RT was slower when this digit was not the same as the visual digit. Greenwald also reported an important interaction between the modality of the interfering stimulus and the modality of the response: interference from the auditory item was more severe when the subject had to say the visual digit than when he wrote it (Greenwald, 1970a, 1970c).

In response to the suggestion that the failures of selection in his experiment were due to the brevity of the messages, Greenwald (1970b) showed that a spoken digit delays RT to a relevant visual digit even with successive stimuli presented at the rapid rate of one item/second. However, this serial RT task cannot be considered a truly continuous performance, since it is carried out in a series of discrete, speeded acts. Perhaps selection becomes most effective only when the primary task is *coherent,* i.e., involves preview of future stimuli and serial grouping of both stimuli and responses (Kahneman, 1970).

Gopher and Kahneman (1971) have documented the importance of a distinction between *reorientation* and *maintenance* of attention in auditory monitoring. Monitoring a continuous list of words for the occasional occurrence of digits is an easy task even in the presence of a competing message to the other ear. It is also easy to report a short list of digits that is presented to one ear, and ignore digits presented to the other ear. Both tasks are combined in our experiments. The subjects first monitor one of two dichotic lists of words and digits for several seconds, reporting the digits heard on the relevant ear, then they hear a cue which defines the relevant ear for the second part of the task. Shortly after that cue, short lists of digits are presented to the two ears. The reorientation of attention after a period of selective listening is quite difficult. Subjects are prone to intrusions and confusions for a few seconds after the reorientation cue. There are pronounced individual differences in the rate of these errors. The lability of selective attention after a reorientation cue is negatively correlated with the proficiency of military pilots (Gopher & Kahneman, 1971) and with the safety record of bus drivers (Kahneman, Ben-Ishai & Lotan, 1973), while the rate of errors in steady-state monitoring is consistently less valid as a predictor of the same criteria.

These observations indicate that it takes some time to change from one selective set to another. Gopher (1971), in a study of eye movements, confirmed the importance of this distinction between orientation (from a neutral, uncommitted state) and reorientation. Reorientation was accompanied by a much larger eye movement than was the initial adoption of an orientation.

In summary, although the selection of inputs is highly effective, it is imperfect. A relevant input on which attention is focused can be processed effectively even in the presence of irrelevant stimulation. However, focusing attention on one message does not completely prevent the processing of stimuli on irrelevant channels. There is much evidence that at least some of these stimuli are analyzed for content. Thus, a stimulus for which there is high readiness will probably be recognized. In addition, any obvious change on any sensory channel will be detected. A few seconds are apparently required for the focusing of auditory attention to become fully effective.

A brief survey of the main theories advanced to account for these facts will now be presented.

BROADBENT'S FILTER THEORY

Broadbent's filter theory is the natural starting point for any discussion of modern theories of attention. Some of the main features of this theory have already been noted, as well as some of the evidence that shows it to be inadequate. Briefly, Broadbent assumed a sequence of three elements: a short-term store (S-system), a selective filter, and a limited capacity channel (P-system). Concurrent stimuli enter into the S-system in parallel, and they are analyzed there for physical features, such as location or tonal quality. There is no definite limit on the capacity of the S-system. The selective filter allows those stimuli that arrive on a designated "channel" into the P-system. A channel is defined by any physical characteristic for which the filter can be set. Thus, location or pitch could both define a channel in audition. Color or size could define a channel in vision.

More elaborate perceptual analyses are carried out in the P-system. This system deals serially with accepted stimuli, and the time spent on each stimulus depends on the amount of information that the stimulus conveys. When the P-system has cleared, the filter allows a new stimulus to enter. Thus, when two stimuli are presented simultaneously, they can be handled successively, but only if the processing of the first is completed before the record of the other in the S-system has decayed. This feature of Broadbent's theory explains the common experience of the "double take," in which one returns to a stimulus that was ignored or not fully processed at the instant of its presentation. Such is the experience of the husband, deeply engrossed in his paper, who first exclaims, "What?" and then, without waiting for an answer, goes on to say, "No, I'm not hungry," as he retrieves his wife's query from an echoic memory.

Filter theory interprets focused attention as setting the filter to select a certain class of stimuli and to reject all others. Irrelevant messages are simply allowed to decay in the S-system without undergoing more advanced processing in the P-system. Therefore, attention is most effectively focused by a *stimulus set,* in which the relevant stimuli are distinguished by one of the simple operations that the filter can perform, e.g., discriminations of location, pitch, and speech-like quality in sounds. Selection is difficult or impossible in the absence of a clear physical distinction between relevant and irrelevant stimuli. Filter theory is supported by the finding that subjects cannot focus attention solely on digits when a mixed array of digits and letters is briefly presented (Sperling, 1960). Similarly, bilingual subjects cannot separate a message in English from a simultaneous message in French if the two messages are spoken in the same voice and originate at the same location (Treisman, 1964a). Selection by semantic class, or by language, requires the subject to adopt a *response set* (Broadbent, 1970, 1971), because the relevant items are defined by a common set of responses rather than by a common stimulus feature. Although Broadbent's (1970) elaboration of his original theory acknowledged that selection by response set is sometimes possible, he presented evidence that response set is generally much less effective than stimulus set.

Filter theory implies that attention cannot be divided, because the P-system performs no parallel processing of discrete stimuli. According to the theory, the apparent division of attention in the performance of concurrent activities is mediated by alternation between channels or between acts, and the rate of alternation is slow. Broadbent (1958) assumed that the minimum dwell-time of the filter is about 300–500 milliseconds. The processing of simultaneous complex messages fails when the processing of the first message which enters the P-system is so prolonged that the traces of the other message decay in the S-system before they can be retrieved.

As initially stated, filter theory was wrong. It will be shown in Chapter 8 that parallel processing of simultaneous stimuli does occur in divided attention. Furthermore, the evidence of the preceding section demonstrates that the content of an irrelevant message is identified, at least dimly and at least some of the time, even when the subject attempts to ignore it. Finally, the idea of a slow-moving filter that selects one stimulus at a time is not viable. Thus, virtually all the predictions of filter theory about what people *cannot* do have been disproved. However, filter theory provides a useful approximation to what people *usually* do. In addition, it has the unique distinction among attention theories of being sufficiently precise to be definitely disproved.

Many of the terms and concepts of filter theory have been widely applied. In particular, the image of filtering as an operation that opens one channel and closes others has been very influential. This image, however, was derived from the study of auditory attention and of the dichotic case in particular. It is not easily applied to visual attention. For example, what defines the channel selected when one reads a book? The analysis of attention presented in Chapter 5 proposes the concept of perceptual unit, or group, as an alternative to the concept of channel.

Another influential idea of filter theory was the concept of a preperceptual memory (the S-system). The temporary storage of unanalyzed sensory information has acquired many names from numerous investigators. Sperling (1960) spoke of a visual image, which he later (Sperling, 1963) renamed Visual Information Storage (VIS), and to which he added an Auditory Information Storage (AIS) (Sperling, 1967). Crowder and

Morton (1969) and Morton (1970a) described a Precategorical Acoustic Storage (PAS), and Neisser (1967) introduced the terms echoic and iconic memory for the auditory and visual stores.

There is general agreement, however, that the precategorical or iconic stores must be distinguished from various forms of post-perceptual short-term memory (e.g., Atkinson & Shiffrin, 1968; Broadbent, 1971). In addition, the basic assumption that unanalyzed material can be stored for several seconds has been questioned (Massaro, 1972; Norman, 1969b). Thus, Norman (1969b) required subjects to shadow one message of a dichotic pair and tested their memory for items presented in the relevant and the irrelevant messages immediately before the interruption of shadowing. There were no important differences between the retention of relevant and irrelevant items, and Norman inferred that both classes of items have access to the same systems of post-perceptual memory. The relation between attention and memory will be discussed again in the next chapter.

TREISMAN'S FILTER-ATTENUATION THEORY

In an attempt to accommodate the evidence against filter theory, Treisman (1960; 1964d) proposed a modification of that theory which Broadbent (Broadbent & Gregory, 1964) subsequently accepted. The modification was simply that filtering is not all-or-none: the rejected message is merely attenuated, not eradicated.

According to Treisman (1960), a sensory message activates hypothetical "dictionary units" in memory. Each unit has a threshold which must be exceeded for perception to occur. The thresholds for highly significant stimuli, such as one's name, are permanently lowered. The threshold for a word which the context makes probable is lowered temporarily. Because of these variations of thresholds, a word of high significance or high probability which is presented in an irrelevant channel can be perceived in spite of attenuation. The assumption of lowered thresholds for significant stimuli was intended to explain Moray's (1959) discovery that subjects often respond to their name spoken on one ear while they shadow a message on the other ear. Temporary alterations of threshold explain the effects of context on the recognition of degraded stimuli (Morton, 1969b; Tulving & Gold, 1963), and also explain Treisman's (1960) finding that shadowing subjects occasionally follow the content of a message which is suddenly switched from one ear to the other. In the terms of signal-detection theory, these effects are mediated by rapid and short-lived criterion changes.

Treisman's modification of filter theory retained the essential idea that attended and unattended stimuli are treated differentially from a very early stage of perceptual analysis. This differential treatment causes a reduction of sensitivity (*d′*) for unattended stimuli. In general, unattended items do not activate the corresponding dictionary units, except when the threshold of one of these units is exceptionally low.

Treisman (1969) later presented a more inclusive treatment of the entire field of selective attention. Two observations were basic to that theory: (1) people can easily focus attention on one input (e.g., the voice on the right), while they have great difficulty in dividing attention between two inputs; and (2) people can easily divide their attention between the various aspects or attributes of a particular input (La Berge & Winokur, 1965; Lappin, 1967), but they encounter great difficulty in focusing on one aspect of a stimulus and ignoring the others (Stroop, 1935; Treisman & Fearnley, 1969).

As was mentioned in the preceding chapter, Treisman (1969) proposed that a single input can be processed by several analyzers in parallel, while the processing of two inputs by the same analyzer is necessarily serial. In a major departure from filter theory, she concluded that divided attention and parallel processing are possible for two simultaneous inputs, but only if they do not reach the same analyzers. Serial processing is mandatory, however, whenever a single analyzer must operate on two inputs.

The main implication of this new theoretical idea concerns divided attention: unlike filter theory, Treisman's analyzer theory permits parallel processing, e.g., of information presented to different modalities. This issue will be considered in detail in the next chapter.

Treisman (1969) retained the filter-attenuation approach to focused attention. She used the concept of analyzer only to explain why any major physical change in the characteristics of a rejected message is invariably recognized (Lawson, 1966; Treisman & Riley, 1969). Such a stimulus is easily detected because it reaches analyzers that are not occupied by the relevant message.

THE DEUTSCH-NORMAN THEORY

An important alternative to filter-attenuation theory was formulated by Deutsch and Deutsch (1963). The evidence that had led Treisman to a moderate revision of Broadbent's theory brought Deutsch and Deutsch to the more radical conclusion that "a message will reach the same perceptual and discriminatory mechanisms whether attention is paid to it or not [p. 83]." They postulated central structures, equivalent to Treisman's dictionary units, but proposed that attention does not affect the degree to which these structures are activated by sensory stimulation. However, each central structure has a preset weighting of importance, which reflects momentary intentions (e.g., animal names are now relevant) or enduring dispositions (e.g., my own name is always relevant). Among concurrently active central structures the one with the highest weighting of importance is selected to control awareness and response. In the terms of signal-detection theory, the importance parameter is a criterion bias favoring the relevant items.

The Deutsch and Deutsch theory locates the transition from parallel to serial processing closer to the ultimate response than does filter theory (see Fig. 1-1 on p. 6). The distinction between the theories is sharpest in the context of divided attention. Filter theory asserts that division of attention among concurrent stimuli is simply impossible, since attention can only be directed to one channel at a time. Deutsch and Deutsch, on the other hand, imply that detection of a relevant signal should be easy whether or not the observer is currently attending to the channel on which the signal is presented. As will be shown in the next chapter, this prediction is not confirmed.

An obvious deficiency of the formulation proposed by Deutsch and Deutsch (1963) is its failure to account for the facts of focused attention which filter theory was designed to explain. They assumed a system that can be preset in advance to favor the recognition of certain stimuli, such as animal names. However, such a system cannot be preset in advance to favor words that will be heard on the right ear, since it has no knowledge of what those words will be. It can only favor a right-ear word *after* all concurrent stimuli have activated the central structures to which they correspond. Thus, the process of selection by stimulus features appears to be more complex than selection by response class. The added complexity should probably make selection by physical features relatively difficult. The evidence of focused attention, however, indicates that stimulus set is far more efficient than response set.

Norman (1968) attempted to reformulate the Deutsch and Deutsch theory to overcome this deficiency. He assumed central units which accept two types of inputs: (1) sensory inputs; and (2) pertinence inputs. The latter are equivalent to the importance weighting proposed by Deutsch and Deutsch. The magnitude of the pertinence input reflects the criterion level for the elicitation of activity in each central unit. At any moment of time the unit with the highest total of sensory and pertinence inputs dominates perception, awareness, and memory.

Norman (1968) explained the operation of stimulus set by assuming that the activation of a recognition unit is a gradual and recursive process. A central unit which is activated by a stimulus on the relevant channel "knows" this fact at an early stage in the process of recognition, and this information causes the pertinence of the unit to increase. With this assumption of recursiveness, Norman's theory explained why stimulus set need not be substantially more difficult than response set. It still failed to explain, however, why stimulus set is actually easier.

Norman (1968, p. 528) emphasized the contrast between his view and Treisman's filter-attenuation theory. Both theories account for the effects of context and word significance in selection by criterion bias. However, Norman also explains filtering as a criterion effect, whereas Treisman implies that discriminability (d') is reduced for items rejected by the filter.

An experiment by Moray and O'Brien (1967) appears to provide a test of Norman's predictions. Subjects were exposed to a dichotic message consisting of letters and digits; they were to attend only to the right ear, and to press a key with the right hand whenever they heard a letter on that ear. Although instructed to ignore the message on the left ear, they were to tap a key with the left hand whenever they happened to hear a letter on that ear. The signal-detection analysis of the results was not entirely conclusive, because of the very low false alarm rate, but it suggested that the criterion for left-hand responses was lower than the criterion for right-hand responses. That is, the number of false alarms on the irrelevant channel was greater than Norman's theory would perdict. In addition, d' was much lower on that channel. Other experiments (e.g., Broadbent & Gregory, 1963; Kahneman, Beatty & Pollack, 1967) have also supported the conclusion that selective attention affects discriminability, contrary to the position of Deutsch and Deutsch and Norman.

One could perhaps attempt to dismiss these results by invoking a distinction between two types of criterion effects, which operate respectively on recognition and on the overt response. In the experiment by Moray and O'Brien, for example, the criterion for recognizing irrelevant words on the left *ear* could be high (low pertinence), while the criterion for making responses with the left *hand* could be low (careless responses). This distinction has some intuitive appeal. If it is accepted, however, the claim that pertinence affects the criterion is robbed of any operational consequences.

NEISSER AND HOCHBERG

Other alternatives to filter-attenuation theory have been proposed by Neisser (1967, 1969) and Hochberg (1970). Neisser's (1967) important text generalized to all areas of perception a theory originally developed to account for the perception of speech (Liberman, Cooper, Shankweiler & Studdert-Kennedy, 1967). According to Neisser's theory, perception is an active process of analysis by synthesis. Thus, one understands a spoken message by covertly reproducing it, and visual percepts are produced by a similar activity of synthesis. Perception is an act of construction, and the role of attention is to select the percepts that will be constructed or synthesized. "On this hypothesis, to 'follow' one conversation in preference to others is to synthesize a series of linguistic units which match it successfully. Irrelevant, unattended streams of speech are neither filtered out nor attenuated; they fail to enjoy the benefits of analysis by synthesis [Neisser, 1967, p. 213]."

Elsewhere, Neisser (1969) summarized his point of view by an image: "If a man picks up a sandwich from a dozen offered to him on a tray we do not ordinarily say that he has blocked or attenuated the others; he simply hasn't picked them up. Naturally he finds out a good deal more about the one he has selected, because he must shape his hand to fit it, to hold it together and so on." In addition, ". . . we might think of him keeping his fingers lightly on the other sandwiches, both before and during his activities with the one he selects, to make sure that nothing untoward is going on." The two passages illustrate the essential point that there is no evidence for the negative view of attention implied by the concept of filtering. Selective attention consists of the allocation of a limited capacity to the processing of chosen stimuli and to the preparation of chosen responses.

In addition to the active process of analysis by synthesis, Neisser assumed the existence of passive systems to perform a preliminary sorting and organization of sensory data. These are "silent" systems whose operation is not represented in awareness. They are responsible for grouping and localization and they routinely watch for critical features of stimulation that may require a redirection of focal attention. The sudden motion of an object is such a feature, and the responsiveness to it is probably innate. In addition, special tests are constructed to detect significant and recurrent stimuli, such as the listener's own name. It is worth noting that the stimuli which most easily redirect focal attention are also those which reliably elicit an orienting response (Lynn, 1966; Sokolov, 1963).

Neisser's theory provides an adequate account of focused attention. It implies a process which selects the relevant stimuli that deserve the effort of perceptual synthesis. Although Neisser objected to the image of a filter, the selection of messages for synthesis is undistinguishable from the operation of a filter. His theory attributes the effects of significance and context to the role of expectations in the process of synthesis, and it assumes a crude and global analysis of rejected messages. Thus, there seem to be no predictions to separate Neisser's view from Treisman's attenuation theory. Indeed, the single difficulty which Neisser conceded in comparing his theory to Treisman's could easily be avoided by a slight reformulation of his position.

Treisman (1964b) had found that a subject can shadow a message to the right ear more easily in the presence of a single competing message to the left ear than with two competing messages, one on the left and one heard in the middle of the head. Furthermore, a pair of interfering messages caused less interference when they were superimposed on a single channel than when they were presented on distinct channels. After describing these findings, Neisser (1967, p. 217) wrote: "While the filter theory can probably accommodate this result rather comfortably, I would not have predicted it from considerations of analysis-by-synthesis. If unattended messages are simply remaining unsynthesized, it is not obvious why a spatial separation between them should make a difference of any kind." In fact, this finding poses no difficulty for Neisser's theory. The theory implies that the effectiveness of selective attention depends on the ability of the pre-attentive mechanisms to segregate the relevant from the irrelevant messages. It is plausible that this task is more difficult when there are two distinct irrelevant messages than when there is only one. On the other hand, two messages originating in the same location are heard as noisy gibberish, which is easily distinguished from the relevant message.

Neisser's theory elegantly dismisses the issue of perception versus response by the simple assertion that the two are undistinguishable, because perception is enactive. In addition, it suggests the interesting possibility that pre-attentive processes and focal processes may follow different rules. The work of Beck (1972; Beck & Ambler, 1972) supports this idea by showing that the relative difficulty of discrimination problems may change in different states of attention (see above, p. 74). The distinction between pre-attentive and focal processes may be related to a distinction recently proposed between two functional visual systems: an orientation system concerned with the perception of space and with the detection of significant events in the periphery of the field; and a central system concerned with fine discriminations (Held, 1968; Ingle, 1967; Schneider, 1967; Trevarthen, 1968). Physiological and comparative analyses of visual function in various animals provide much support for this distinction.

There remains a significant difficulty in Neisser's treatment of focal and pre-attentive processes. He identified detailed perceptual analysis with focal attention, and focal attention with awareness. This is implausible, since complex psychomotor skills, such as driving, are often performed with little awareness, although they certainly require detailed perceptual analysis.

Hochberg (1970) presented a similar view of selective attention which could avoid this difficulty. He described perception as the confirmation of a changing set of expectations, concerning future phonemes when one listens to speech, or the foveal image that would be produced by possible movements of the eye when one looks at a picture. He also assumed that the perceiver normally stores in memory only sets of expectations that have been confirmed. Stimuli that are not matched to prior expectations are very rapidly forgotten, unless they are exceptionally salient. An intention to focus attention on one message causes detailed expectations to be produced for that message alone. Irrelevant messages are not expected in detail, and are forgotten almost as soon as they are heard. The production of expectations, of course, is very similar to Neisser's active synthesis.

Hochberg's approach is similar to Neisser's, but he implies a separation of detailed perceptual analysis from awareness. Detailed perception depends on the generation of confirmed expectations, but awareness of what one perceives also depends on whether the results of perceptual analysis are stored in memory. If a stimulus is anticipated, but immediately forgotten, there will be no awareness although perception may be detailed. Thus, Hochberg would probably describe driving as a case of detailed anticipation with immediate forgetting. This description appears more appropriate than a statement that driving is controlled by crude and global mechanisms, as implied by Neisser's theory. Another heuristic advantage of Hochberg's formulation over Neisser's is that the concept of expectation is more readily translated into the language of signal-detection theory than analysis-by-synthesis. However, Treisman (personal communication) has observed that detailed expectations cannot be quite as important as Hochberg's treatment would suggest. Thus, it is possible to shadow a message even if it consists of unrelated words, precluding the formation of expectations.

It may be noted that Freud's analysis of attention in the famous seventh chapter of *The Interpretation of Dreams* was somewhat similar to Hochberg's proposal. Freud discussed the attachment of attention-cathexis to objects of perception or to objects of thought, and the hypercathexis that allows them into consciousness. Freud adopted a positive view of focused attention, in which selective attention is the active elaboration of chosen ideas, rather than the inhibition of others (Freud, 1900; Rapaport, 1967; Schwartz & Schiller, 1967, 1970).

An important notion in Freud's view was that the total quantity of attention cathexis available at any one time is limited, and that the amount of attention demanded by an object of thought or perception depends on how it is elaborated in cognitive activity. This view implies that the limitation on what man can perceive depends on how he perceives, and on what he does with his percepts. Freud's theory of attention was an effort theory.

A THEORETICAL SYNTHESIS

In the present section the analysis of attention that was developed in Chapter 5 (see Fig. 5-1) is reviewed and related to the theories discussed in preceding sections.

Unit Formation

The array of stimulation is sorted into integral units, which maintain their identity through subsequent stages of perceptual analysis. Subsequent operations are applied to these units: units are allocated capacity at the stage of figural emphasis, and units or features of units activate the recognition stage. An operation at one of these later stages can fail because the earlier grouping stage did not isolate the relevant unit. The suffix effect, which will be discussed below, is an example of a failure of selection due to grouping.

The idea of an initial grouping stage is adopted from Neisser's notion of pre-attentive mechanisms. It applies both to vision and audition. For example, letters printed in red may form a natural group within a larger array of letters printed in black. Similarly, a phrase spoken by a particular voice and originating in a particular location constitutes a natural auditory unit in the cocktail-party situation. In both vision and audition location in space is the primary determinant of unit formation: sounds that originate in a particular location tend to be grouped, as do clustered visual objects.

According to this analysis, attention is focused by selecting among available perceptual units (objects or events) those units to which most capacity should be allocated. By measuring grouping, we may be able to predict the outcome of selective attention (Beck & Ambler, 1972; von Wright, 1968, 1970; Williams, 1966). Furthermore, a careful study of the laws of unit formation is needed to overcome a serious weakness of filter theory: its failure to explain why certain physical features of stimuli are effective in defining "channels," while others are not.

Figural Emphasis

Capacity is allocated in graded fashion to various groups. The frequent demonstrations that selective attention usually results in attenuation rather than in total blocking suggest that figural selection is not all-or-none. Parallel processing of different units is possible, but perception draws on a common pool of capacity, and the ability to carry out detailed analyses of several units is limited.

Broadbent's theory assigns the functions of both grouping and selection to the filter. However, it appears essential to separate these functions, since they follow different rules. A major difference is the degree of voluntary control over the two stages: with rare exceptions, unit formation is largely controlled by involuntary and psychologically silent processes, while the allocation of capacity is immediately responsive to momentary intentions.

Although the allocation of capacity is generally effective, it is not perfect. Some capacity is allocated to the processing of irrelevant stimuli, and the processing of a selected stimulus is rarely as effective in the presence of other stimulation as when the same stimulus is shown alone.

Recognition and Interpretation

The present treatment suggests a distinction between an early stage at which sensory information makes contact with recognition units, and a subsequent stage at which a coherent set of interpretations is selected for some of the objects in the field. It was assumed that the interpretation stage has a threshold. If no recognition unit is sufficiently activated, there may be no interpretation for a particular object. The hypothesis that figural emphasis controls the quality of the input to recognition units implies that most items on an irrelevant "channel" will remain uninterpreted. However, if the readiness for a particular item is particularly high, that item is likely to be consciously recognized even when it was not initially favored at the stage of figural selection. Hearing one's name mentioned in a neighboring conversation is an example. In addition, the activation of a recognition unit can have behavioral consequences even when it does not yield a perceptual interpretation. Thus, significant words sometimes elicit emotional responses without attracting attention and without gaining conscious interpretation (Corteen & Wood, 1972).

Responses to the Rejected Channel

According to the theory of effort presented in Chapter 2, the subject in a task of focused attention allocates only spare capacity to the continuous monitoring of irrelevant inputs. The amount of spare capacity varies inversely with the demands of the primary activity. Consequently, the rejection of unwanted inputs should be most effective when the primary task requires great effort. Zelnicker (1971) has confirmed this conclusion in her study of delayed auditory feedback.

The results of Corteen and Wood (1972) and Lewis (1970) indicate that a stimulus on a rejected "channel" may affect some aspects of behavior if it activates recognition units. In addition, such a stimulus may be consciously perceived if it causes a reorientation of attention. The conditions for such a reorientation have been described in the context of the orienting response. A sudden and intense change will elicit an OR. In addition, the activation of certain recognition units usually causes an orientation. The effectiveness of a subject's name as an elicitor of OR's is well documented in the Russian work. Stimuli that will cause an OR when presented on an attended channel are also the most likely to be detected when presented on a rejected channel.

Responses to an item on a rejected channel are not always associated with an OR. Sometimes, an item on a neglected channel is perceived because it conforms to expectations, not because it violates them. An example is Treisman's (1960) observation that subjects will follow an attended message when it is switched from one earphone to the other. This cannot be explained by the occurrence of an OR. Here, a stimulus that was expected is perceived by a grouping effect. An important difference between this case and the responses to orientation stimuli on the rejected channel is that Treisman's subjects were usually unaware that they had switched channels. On the other hand, a subject who detects a tone or a mention of his own name on the previously unattended channel is immediately aware of the reorientation of attention.

Consciousness and Expectations

According to the present model, we are aware of perceptual interpretations, but we are aware neither of the activity nor of the output of earlier stages of processing. Since it is assumed that attention to a stimulus object increases the likelihood that the object will be fully interpreted in perception, it follows that perceptual effort and awareness should be correlated.

Stimuli on the rejected channel do not attract much effort. Consequently, the perceptual interpretations that correspond to these stimuli are impoverished, and the awareness of them is slight. Thus, we consciously perceive only very few of the events on a rejected channel. Since the conditions for awareness and for storage in long-term memory are closely related (Posner & Warren, 1972), we also remember very little of what happened on that channel.

Contrary to the position taken by Hochberg (1970), it may be argued that it is the violation of expectations, rather than their confirmation, which promotes conscious experience. We soon lose our awareness of the ticking of the clock, although the expectation of continued ticking is continuously confirmed. It is the stopping of the clock of which we become aware. Similarly, we are keenly aware of driving a car only when expectations are violated or when the situation is changing so rapidly that no reliable expectations can be formed. These are conditions that require considerable effort.

The present approach to focused attention entails a number of predictions that distinguish it from other theoretical positions. It shares with Neisser's theory a common emphasis on the role of pre-attentive mechanisms that constrain the subsequent allocation of attention. An experiment that illustrates these effects is discussed in some detail in the next section.

Groups or Channels

An instructive failure of selective attention can be observed in the following experimental situation: a subject hears seven relevant digits, preceded by the irrelevant and redundant digit "zero." He is to repeat only the seven relevant digits. In spite of the instruction to ignore the "zero," the memory for the relevant digits is markedly impaired (Dallett, 1964). This impairment has been called the *stimulus prefix effect.* There is also a *stimulus suffix effect,* where memory is impaired by the presentation of an irrelevant and redundant "zero" at the end of the list. The two effects represent a clear failure of selection: the subject is forewarned, but he is nevertheless incapable of rejecting the interfering irrelevant stimulus.

The boundary conditions for the occurrence of the suffix effect have been investigated in a series of careful studies (Crowder, 1967, 1969, 1971; Morton, 1970a, b; Morton, Crowder & Prussin, 1971; Morton & Holloway, 1970). It was found that memory can be disrupted by a suffix that is not a digit, or even a meaningful word: any speech sound uttered in the same voice as the relevant message causes a suffix effect.

Several manipulations were found which abolished or reduced the suffix effect: a visual stimulus does not cause the effect, nor does a sound that is not speech-like. The disruptive effect is reduced when the suffix is spoken by a different voice than the relevant list, or when it appears to originate from a different location.

Morton and Crowder interpreted these results by a theory of the precategorical acoustic storage, or PAS. The ineffectiveness of a visual suffix was accepted as evidence that interference occurs within an auditory system. The unimportance of semantic content indicated that this system is precategorical, i.e., located upstream of the word recognition system. The role of similarity between suffix and list was interpreted in the context of a filter theory: items that arrive on the same channel enter the same system of storage, but the filter can be set to preclude entry of stimuli that arrive on other channels. Contrary to Broadbent's assumption that the filter is encountered after all stimuli are accepted into the

S-system, the observation that the suffix effect can be prevented led to the conclusion that PAS is located after the filter (Morton, 1970a, b).

The stimulus *prefix* effect was addressed by Neisser in very different terms (Neisser, Hoenig & Goldstein, 1969). In the context of a theory of analysis-by-synthesis, the rhythm of the presentation was assumed to dominate the perceived organization of the digit list: "The stimulus string consists of eight digits and is heard as such; all eight take up space in the resulting construction—even if one was redundant—because they were heard as a single utterance [Neisser, Hoenig & Goldstein, 1969, p. 425]." It follows that the prefix effect should be eliminated by altering the perceived structure of the string. This was successfully achieved by presenting the prefix in a different voice than the list. Moreover, there was no disruptive effect when the prefix consisted of the sequence "zero, zero, zero." This prefix constitutes a group, which can be easily segregated from the relevant material.

This study illustrates the superiority of a formulation of selective attention as an operation on perceptual units rather than on channels. It is surely unreasonable to assume that the triad "zero, zero, zero" defines a channel, whereas a single "zero" does not. The triad, however, provides an adequate group.

The theory of attention that was summarized in the preceding section explains the results of this study by the operation of a pre-attentive process of unit formation: interference occurs only within a perceptual unit, and it can be prevented if the potentially interfering material is included within a unit of its own. This interpretation applies to the suffix effect investigated by Crowder and Morton, as well as to the prefix effect studied by Neisser *et al.* Furthermore, the same rule is expected to apply in vision as well as in audition. In contrast, the Crowder-Morton hypothesis explains only auditory suffix effects, in terms of interference with a precategorical acoustic storage.

To test this conception, Ulric Neisser and I tried to obtain a visual equivalent of the suffix effect, and also to reduce that effect by a manipulation of grouping structure.

Subjects (N = 64) were shown a clearly legible array of six relevant digits for half a second, and they immediately wrote the digits they could recall. A visual "suffix" was shown on most trials, next to the far right item. The digit "zero" appeared only as a suffix, and the subjects were given advance exposure to all the suffixes that were used. Figure 7-1 shows several of the displays and indicates the number of errors that were made in the fifth and sixth positions for each of these displays. As in the case of the auditory suffix, the detrimental effect of the visual suffix was most pronounced in the two positions closest to the interfering item.

Figure 7-1 shows that interference is pronounced when the suffix

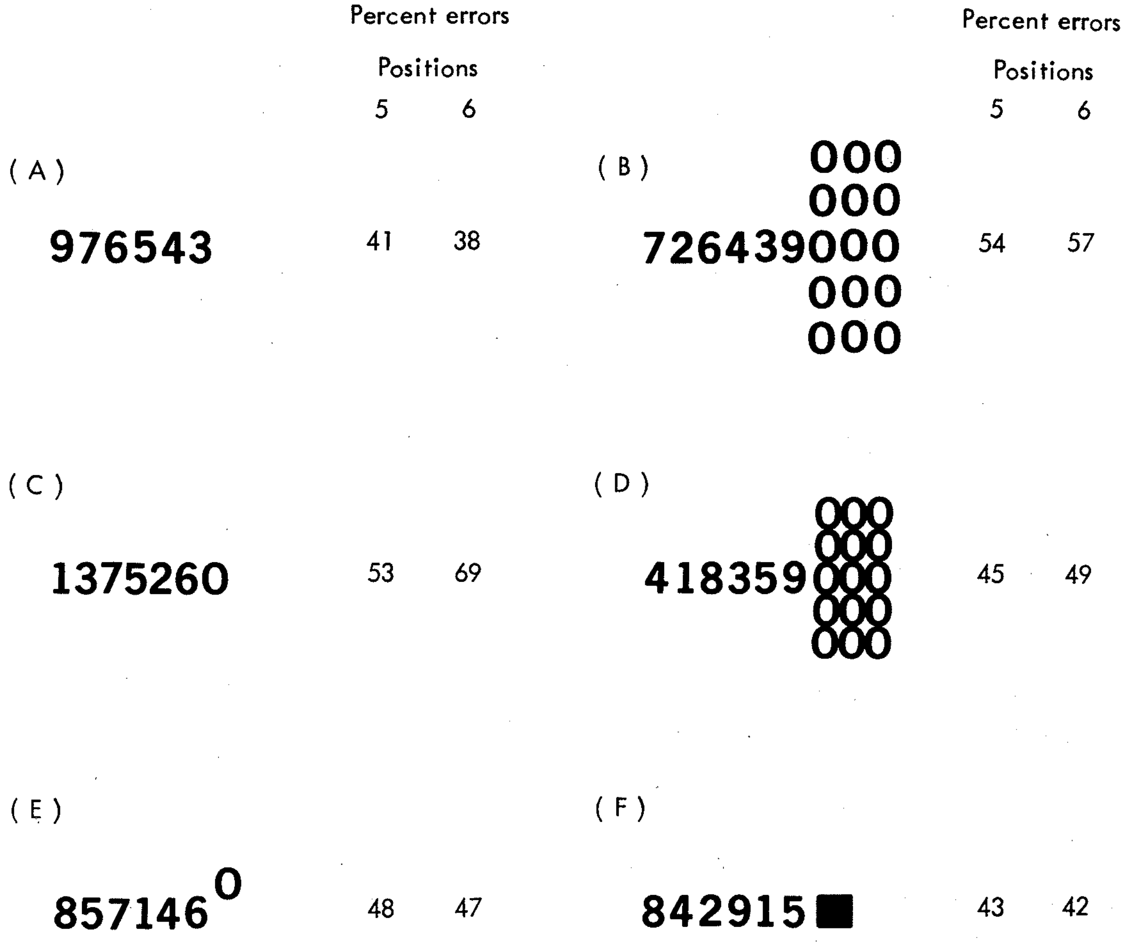

FIGURE 7-1
Effects of different visual suffixes.

is embedded within the perceptual group of relevant material. Interference can be prevented or reduced by removing the suffix from the relevant group, as in E, or by embedding it into another group, as in D.

This experiment has been discussed in detail because it provides a suggestive prototype of focused attention tasks. As in other attention tasks, the subject is instructed to respond to some stimuli and ignore others. Whether he can do so depends on a grouping process which precedes and constrains the allocation of attention. Attention operates by emphasis rather than by filtering: the suffix is always "seen," but it is seen as background rather than as figure.

The results of Figure 7-1 demonstrate the futility of attempts to explain all effects of attention by a bias on the control of responses. The pertinence of all suffixes was surely very low, yet some caused interference while others did not.

It is also difficult to analyze this visual example of focused attention in terms of a filter that selects among channels. The difficulty illustrates the prevalence of auditory concepts in modern discussions of attention: the phrase "attend to a channel" suggests a sense of temporal continuity which is inappropriate to the perception of a stationary visual scene. In the context of attention, the most important difference between vision and audition is that auditory perception requires spatiotemporal grouping while the visual analysis of unmoving objects involves only spatial grouping. Auditory attention to one message in a medley is analogous to visual attention to one dancer in an ensemble, a vastly more complex case than that of our experiment.

It is tempting to speculate that the modern study of attention could have taken a different course if Broadbent (1958) had been concerned with how one sees dancers rather than with how one hears messages. Since it is surely possible to see many dancers while attending to one, the concept of a filter that allows inputs into perception in single file might not have been proposed. Deutsch and Deutsch (1963), on the other hand, might not have argued that attention does not alter perceptual analysis, because the difference between the perception of the prima ballerina and of lesser dancers is too obvious to be ignored. Finally, the traditional emphasis on spatial organization in vision would have led much sooner to a discussion of the pre-attentive mechanisms that control attention.

Review

Selective attention to inputs is the allocation of capacity to the processing of certain perceptual units in preference to others. The focusing of attention is very effective in preventing irrelevant stimuli from interfering with the primary task, but there is evidence that irrelevant stimuli are sometimes processed at least up to the level of recognition units. In addition, one often perceives such stimuli, if they tend to be grouped with the message, if they represent obvious physical changes, or if they are both familiar and highly significant. These observations are consistent with the hypothesis that spare capacity is continuously allocated to the processing of perceptual units that are not emphasized.

The present theory assumes a mechanism of unit formation, which performs some of the functions that Neisser attributed to pre-attentive mechanisms. The stage of figural emphasis selects some of the units for especially detailed processing, much in the manner of Broadbent's filter. The emphasis on the selected messages is a matter of degree, as suggested by Treisman's concept of attenuation. The distinctive predictions of the present theory are that the effectiveness of selection depends on the ease with which relevant stimuli can be segregated at the stage of unit formation, and that the effectiveness of rejection of irrelevant stimuli depends on the amount of capacity demanded by the primary task.

8

Attention Divided Among Inputs

The classic question of whether attention is unitary can be rephrased in modern terms: can two simultaneous but unrelated inputs be processed at the same time? The various theories of attention reviewed in the preceding chapter imply different answers to this question.

Broadbent's filter theory proposed that inputs are processed in parallel in the S-system of sensory registration and preliminary storage and at the elementary level of analysis which controls the setting of the filter. Beyond the filter, inputs are handled serially. Two simultaneous inputs may both be perceived and responded to, but not at the same time. One is processed first, and the filter only later retrieves the other item from the S-system of storage. If processing the first stimulus in the P-system takes too long, the second will be lost from the S-system.

Deutsch and Deutsch (1963) and Norman (1968) did not deal directly with the divided attention issue. Their treatment of focused attention assumed that parallel processing normally occurs at all levels of perceptual analysis, with a bottleneck that controls entry to awareness, response selection, and permanent memory. Subsequently, Norman supported the idea of a limited capacity for the systems of perceptual analysis (Norman & Rummelhart, 1970) and memory (Lindsay & Norman, 1969).

Neisser (1967) assumed parallel processing at the pre-attentive level, but he treated focal attention as unitary. Furthermore, the idea that speech is analyzed by synthesis appears to imply that only one verbal input can be synthesized at a time.

Treisman's (1960) attenuation concept implied that some parallel processing of concurrent inputs occurs even when attention is deliberately focused on one input. Later she argued that parallel processing of simultaneous stimuli is possible in different analyzers, while serial processing is necessary within a single analyzer (Treisman, 1969).

The discussions of figural emphasis and of effort in previous chapters suggests that parallel processing of simultaneous inputs is possible. However, parallel processes that impose heavy demands on the limited capacity are likely to interfere with one another.

We will first examine some experiments in which the processing of simultaneous stimuli was either seriously impaired or obviously serial, then turn to other experiments in which processing was demonstrably parallel. Effects of effort and modality are discussed in the final sections.

Concurrent Messages and the Split-Span Experiment

A classic case of inability to process simultaneous sensory messages in parallel was the "personal equation" of nineteenth-century astronomers (Boring, 1950). Astronomers who endeavored to time the crossing of stars by coordinating a visual event to the beat of a clock discovered that they could not agree on their judgments. They eventually traced the difficulty to the irresistible tendency of any observer to focus his attention primarily either on the star or on the beats of the clock. Simultaneous stimuli on the two modalities were not perceived simultaneously: the attended one was perceived as having come sooner. This phenomenon became known as the law of prior entry, and it played an important role in early experimental studies of attention (James, 1890, Chap. 13; Titchener, 1908, p. 251). This phenomenon was used to demonstrate the unitary character of attention and the impossibility of dividing it among concurrent events. A careful recent experiment has confirmed the existence of the effect (Sternberg, Knoll & Bates, 1971).

There have been many other recent studies of apparent simultaneity (see Ladefoged & Broadbent, 1960; Fodor & Bever, 1965; Kristofferson, 1967; Moray, 1969b; Reber & Anderson, 1970). The common interpretation of systematic errors in judgments of simultaneity continues to be in terms of limitations of human capacity which impose serial processing at some stage of analysis or decision. The results and the models, however, vary widely (see Sternberg & Knoll, 1972, for a detailed review).

Prior entry was originally investigated because the demands on the nineteenth-century astronomer appeared to exceed his capacity. The modern investigations of the problem were prompted by the difficulties of another overloaded functionary: the air-traffic controller (Broadbent, 1952, 1954a; Mowbray, 1953, 1954; Poulton, 1953; Spieth, Curtis, & Webster, 1954; Webster & Solomon, 1955). The common finding in these studies was that listeners either completely fail to deal with simultaneous messages or at best handle them successively.

Broadbent (1954a) invented an experimental task which he used to demonstrate the successive handling of simultaneous stimuli. The subject in the *split-span* experiment is presented with two lists of digits simultaneously and reports what he recalls from the presentation. In a dichotic presentation, for example, he may receive the sequence 7-2-8 to one ear, and 9-4-5 to the other. In other variants of the split-span design, auditory items may be presented simultaneously on two external speakers, or an auditory item may be paired with a visual item (Broadbent & Gregory, 1961, 1965; Madsen, Rollins & Senf, 1970). When the presentation rate is faster than about one pair/second, these designs produce the same result: subjects' reports tend to group all items that have arrived on one channel (defined by ear, location, voice, or modality), followed by the items from the other channel. Subjects who are required to report the items in pairs (e.g., 79-42-85 in the example above) make more errors than when they are allowed to report channel-by-channel. Order information, in particular, is often lost in pair-wise recall (Bryden, 1962, 1964; Moray & Barnett, 1965). The difficulty of pair-wise recall decreases markedly with prolonged practice (Moray & Jordan, 1966), but the task always remains difficult.

The split-span experiment has produced three main findings. (1) The task can be performed. Although subjects' performance with such short lists is impaired, it is often adequate. (2) Successive, not simultaneous items tend to be grouped in recall. (3) In particular, items presented on the same channel or in the same modality tend to be grouped. These findings suggested to Broadbent the image of a filter which selects a channel, stays on that channel until the termination of its message, and then switches to accept the second message, which was stored meanwhile in the S-system.

An alternative interpretation is that the preferred order of report is determined by perceptual grouping. If items are perceptually grouped by source or modality, the most advantageous order of report will be compatible with this spontaneous organization. The tendency to group successive rather than simultaneous items also represents a law of grouping. Savin (1967) presented subjects with two successive pairs of digits, all four digits spoken in the same voice and originating at the same place. His subjects almost invariably grouped successive rather than simultaneous items in their reports. Thus, the normal mode of organization for auditory stimuli is sequential. Although this was not its original purpose, the split-span experiment has provided valuable information concerning Gestalt-like rules in auditory perception.

The tendency to report items by channel can be overcome by other grouping factors. This was first shown by Gray and Wedderburn (1960). They presented the three syllables of a word (e.g., extirpate) or the three words of a brief phrase (e.g., mice eat cheese) in alternation to the two ears (e.g., right-left-right), and simultaneously alternated a list of three digits (left-right-left). They found that subjects' reports followed content rather than ear of arrival. Similar results have been obtained in many other experiments (e.g., Bartz, Satz & Fennell, 1967; Broadbent & Gregory, 1964; Yntema & Trask, 1963). This effect of content is limited to dichotic presentation; when the series are presented on different modalities, report by content almost never occurs (Madsen, Rollins & Senf, 1970).

The content effect in the split-span design is probably related to the finding that subjects who are instructed to shadow by ear are nevertheless affected by the continuity of content (Treisman, 1960). It has already been mentioned that semantic factors can affect perceptual organization. In addition, grouping by content in the split-span design also facilitates retrieval. Subjects who attempt to report by channel must produce awkward sequences such as mice-three-cheese, six-eat-two, and organization by content could be imposed at retrieval to avoid such sequences (Broadbent & Gregory, 1964; Sanders & Schroots, 1968).

The question of how attention affects storage in the split-span design has been studied by Bryden (1971). His subjects were to actively rehearse one series (called *A*, for attended) and to ignore the other (*U*, for unattended). They were also to report both series in a specified order, with either the attended or the unattended series first (i.e., the orders were *UA* or *AU*). The striking result was the difference in the shape of the serial position curves for the *A* and *U* groups. As may be seen in Figure 8-1, the serial position curve is flat for the *A* group, but there is a pronounced recency effect with *U* items. Significantly, this result occurs regardless of the order of report.

Another interesting feature of Figure 8-1 is that the order of report (*AU* or *UA*) has less effect on the *U*-message than on the *A*-message. The *A*-message is more susceptible to output interference, the disruption of memory which is caused by the activity of recall. This finding is consistent with the idea that the *U*-message is stored as an acoustic rather

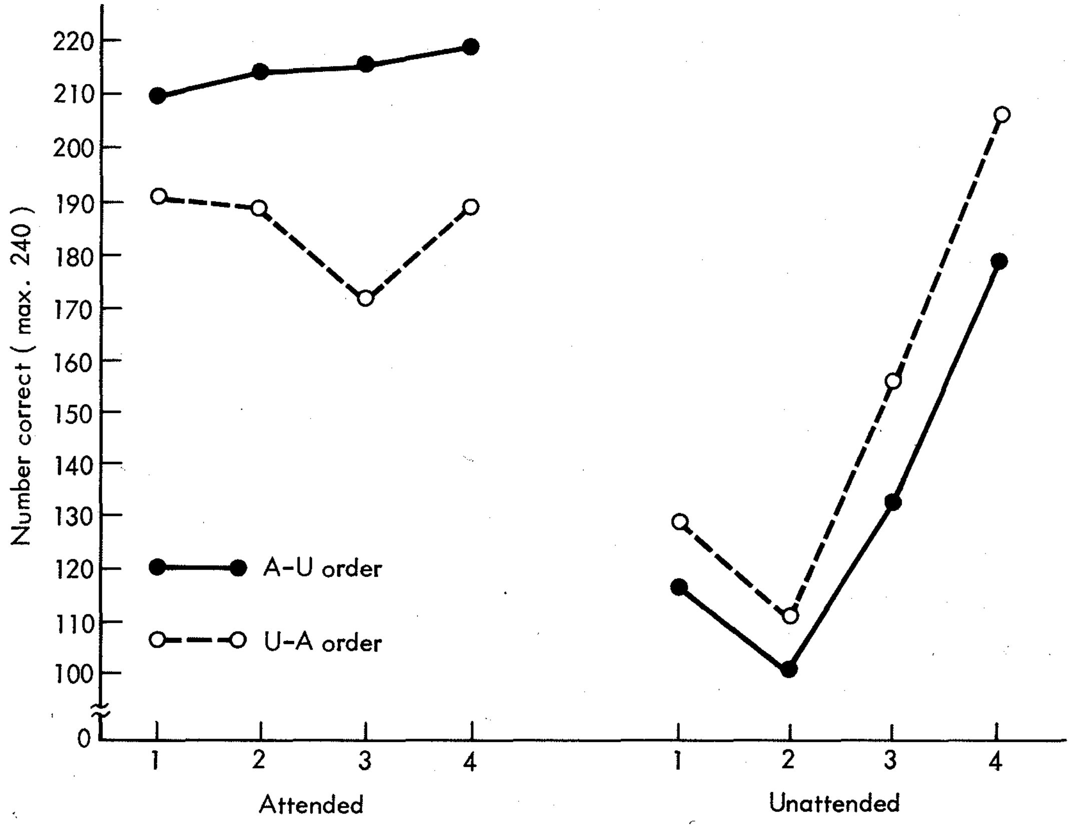

FIGURE 8-1
Recall as a function of attention and order of report (Bryden, 1971, with permission).

than as an articulatory code. Perhaps subjects "attend" to a message by a form of enactive encoding, or rehearsal (Murray & Hitchcock, 1969; Neisser, 1967) which alters the nature of the memory trace, and also strengthens it.

Bryden's study is especially noteworthy because of the novel use of attention as an instruction variable, but its conclusions concerning the nature of storage have been challenged. The observation of a pronounced recency effect is consistent with the idea that the unattended message is stored in a precategorical store, but it provides no conclusive proof. A similar recency effect can be obtained with visually presented words, which are probably "read" at the time of exposure (Corballis & Luthe, 1971). Massaro (1972) has argued that the subjects in Bryden's experiments perceived all items as soon as they were shown, and that the difference between the *A* and the *U* serial position curves was due entirely to rehearsal.

In summary, the split-span experiment has shed less light on theoretical issues than was originally hoped. Certainly, subjects prefer to group their responses in a manner reflecting the perceived organization of the input, and they perform best when allowed to do so. However, there is no evidence that subjects *must* respond in this manner, nor that they cannot perceive simultaneous items in parallel.

FAILURES OF DIVIDED ATTENTION

A striking failure of parallel processing was reported by Colavita (1971). His subjects were instructed to press one key to a light flash and another key to a tone. The subjects expected a single event on each trial, but on some trials both the light and the tone were presented. These occurrences were attributed to equipment malfunction. On 49 of 50 conflict trials (five each for ten subjects), subjects pressed the "light" key alone. On the single trial when the "tone" key was pressed, the subject apologized for his mistake! The subjects were unaware that the tone had been presented on 17 trials. For man, a visual stimulus is clearly dominant over a concurrent auditory stimulus, and it captures both awareness and response. Colavita observed the opposite pattern in nocturnal animals.

Most studies of divided attention have used verbal material. For example, Mowbray (1953), found that subjects could not listen to one story while reading another. On a subsequent test of comprehension of the two messages, the poorer score was consistently near chance level. Despite the intention to divide attention, subjects were apparently focusing on only one of the messages. In a subsequent study, Mowbray (1954) simultaneously presented an auditory and a visual message, which were to be used in a complex task. His subjects were unable to use the simultaneous messages and usually denied noticing the simultaneity. "Many were vehement in their denials and expressed outright surprise, and in some instances, sheer disbelief that such had really been the case [p. 90]." In a simulation of the air-traffic controller's task, Webster and Thompson (1954) also observed very poor handling of simultaneous auditory messages, except when these were highly redundant.

Subjects have also been instructed to shadow a continuous auditory message in one ear and to note for later recall an isolated word presented either to the other ear (Mowbray, 1964) or visually (Mowbray, 1962). Shadowing was usually disrupted by the presentation of the critical word, and the disruption was more severe when that word was spoken than when it was shown visually. Treisman and Geffen (1968) also observed interference with the shadowing of a message to one ear when the subject detected a target word in a concurrent message to the other ear. The word that coincided with a target item was frequently missed in shadowing.

A study by Moray and O'Brien (1967) provides a crucial observation concerning the limitations of divided attention. Moray and O'Brien presented dichotic messages consisting of 90 percent digits and 10 percent letters at a rate of 100 items/minute in each ear; the subject pressed a key with the appropriate hand whenever a letter was heard on either ear. A striking result occurred when two letters were simultaneously presented to the two ears: subjects pressed at least one key on 99 percent of such occasions, but they pressed both keys on only 17 percent of occasions. In a subsequent series of experiments, Moray (1970a, b) obtained essentially the same results in the detection of transient increments of loudness in tone series. Again, when two simultaneous targets were presented, the listener was very likely to respond to one but unlikely to respond to both. These results can be stated in correlational terms: there is a strong negative correlation between responses to concurrent targets on the two ears.

Shaffer and Hardwick (1969b) have reported a monitoring experiment rather similar to Moray's. Their subjects reported the successive repetition of the same word in either of two dichotic messages. Shaffer and Hardwick concluded that some processing of the two messages was possible because subjects detected about 60 percent of these targets. However, there were systematic sequential dependencies between successive items: if a subject had detected a target on one ear, he was likely to detect an additional target on that ear, and he was also likely to miss a target on the other ear. The positive correlation between detections on one ear and the negative correlation between ears suggest that subjects were not dividing their attention equally between the two ears. At any time in the task they were listening more to one ear than to the other.

Moray (1969b) was led by his observations to a modified version of filter theory. He postulated a filter that can alternate very rapidly between channels, as long as no stimuli of special significance are detected. When an important stimulus is recognized, the filter remains locked on the channel where that stimulus arrived until its processing is terminated. These hypotheses explain why a single target is easily detected in divided attention, while an either-or pattern of detection is approximated with simultaneous targets. However, it has been pointed out that performance with such targets is actually too good to be explained by a strict application of Moray's time-sharing theory (Treisman, 1972). Another difficulty for Moray's theory arises because of the extremely important role that it assigns to the timing of stimuli: if two targets are presented in slight asynchrony, the one presented first should always be detected. In fact, the precise synchrony of inputs does not appear to be particularly important in divided attention (Treisman & Davies, 1972). When two auditory targets are presented in near synchrony, the factor of ear dominance is the primary determinant of which is detected, rather than the precise temporal relations between the onsets of the targets (Avner, 1972).

EXPERIMENTAL TESTS OF THE DEUTSCH-NORMAN THEORY

A central issue among theories of attention concerns the effects of inattention on perceptual analysis. Several theories assume that the analysis of unattended items is impaired or precluded (e.g., Broadbent, 1958, 1971; Moray, 1969b; Neisser, 1967; Treisman, 1960, 1964d, 1969). The analysis of attention in this book also adopts this position. On the other hand, other theorists have assumed that attention does not affect the contact of sensory information with recognition units (Deutsch & Deutsch, 1963; Keele, 1973; Norman, 1968). In that view, attention merely determines which of the currently activated recognition units will be allowed to control awareness and response.

The two critical experiments in this area are due to Treisman. In the initial study, Treisman and Geffen (1967) attempted to determine whether selective attention operates on perception or response. They reasoned that filter theory and the Deutsch and Deutsch theory imply different predictions for the following experimental situation: a subject is required to shadow all items arriving on a designated ear and to perform an additional response (tapping) to some items, regardless of their ear of origin. According to Deutsch and Deutsch, a critical item should elicit a response regardless of the ear on which it is heard, because the corresponding recognition unit is preset for it. According to filter theory, on the other hand, the requirement to shadow the message presented to one ear prevents the allocation of attention to the processing of items on the other ear, and therefore precludes the recognition of target items on that ear. In other words, filter theory asserts that a listener cannot comply with the instruction to divide attention between the two channels, while the Deutsch and Deutsch theory asserts that he can.

The results confirmed the prediction derived from filter theory. Treisman and Geffen (1967) reported that subjects detected 87 percent of the target words in the attended message, but only 8 percent in the unattended message. When instructed to tap to a word (e.g., rite) but not to its homophone (e.g., write), subjects were able to use contextual cues to avoid tapping to incorrect homophones only in the attended message. Context had virtually no effect on the detection of target words in the rejected ear.

Deutsch and Deutsch (1967) did not accept this experiment as critical evidence against their theory. They pointed out that a subject was required to perform two tasks, repeating and tapping, in response to target items on one ear and only one task in response to critical items on the other ear. This difference could be reflected in the importance attached to critical items on the two ears, with a consequent bias in favor of the shadowed message.

To overcome this criticism, Treisman and Riley (1969) required subjects to shadow one of two dichotic lists of computer-synchronized digits and to detect occasional letters on either ear. The ingenious feature of the design was the response that the subject was to make to a target item on either ear: he was to immediately stop shadowing. Thus, the response to a critical item was the same, regardless of the ear on which is was heard. The subjects detected 76 percent of letters on the attended ear, and 33 percent on the other. The large bias in favor of the shadowed message provides strong evidence against the Deutsch and Deutsch theory (1963, 1967). However, it should be noted that selectivity was less impressive than in the Treisman and Geffen study. This result would be expected by a theory which emphasizes grouping effects. The use of computer-synchronized digits eliminates most factors essential to the formation of effective perceptual groups, and thereby hampers selection.

In other conditions of the same experiment, Treisman and Riley (1969) observed that critical letters which differ in voice from the background digits are always detected on the unattended channel. This effect of voice quality relates to Lawson's (1966) finding that listeners easily detect a tone on the rejected ear. As was noted in the preceding chapter, such results are consistent with filter theory, which assumes that all stimuli are tested on obvious physical characteristics.

Treisman's experiments demonstrate that attention cannot be divided between concurrent stimuli if the listener is biased toward one channel by the instruction to shadow one of the messages. The bias favoring the shadowed message overcomes the effects of the relevance of designated targets, such as the letters in the Treisman-Riley study. Another demonstration of attentional bias was offered by Weg (1971) in my laboratory. Subjects listened to dichotic messages, each ten words long, presented at a rate of two pairs/second. The recognition of *right-ear* words was tested, as in the focused attention experiments described in the preceding chapter. In addition, subjects were required to note the occurrence in the *left-ear* message of one or two target items, which they were asked to recall immediately after the presentation of the message. Three types of target items were used: (1) words belonging to a content category, such as animal names; (2) digits; (3) isolated digits in a male voice inserted in a message spoken by a female. Subjects were paid a substantial bonus for successful recall of critical left-ear words and were paid at a lower rate for recognizing right-ear items. They were penalized for mistaking left-ear words as familiar in the recognition test.

The subjects were highly successful in the recall test, remembering over 90 percent of the critical left-ear items in all three conditions. However, their ability to selectively recognize words presented on the right ear was severely impaired. In conditions (1) and (2), monitoring for content and for digits, subjects were unable to prevent massive intrusions of left-ear items in the recognition test. Among the words that they identified as having been heard on the right ear, only 40 percent were in fact on that ear, 44 percent were left-ear words, and 16 percent were unpresented distractors. Performance was better in the condition (3), where critical items were identified by voice quality. In that condition, 53 percent of the recognized items had been heard on the right ear, 34 percent were left-ear items, and 13 percent were distractors.

The high rate of intrusions in the content conditions is not easily accommodated by the theories of Deutsch and Deutsch or Norman: the prediction from this theory is that a listener should be able to attach high pertinence values both to right-ear items (when they occur), and to left-ear animal names (in advance), thereby preventing intrusions of irrelevant items from the left ear. The experiment demonstrates that subjects cannot perform in this manner. When expecting an important item on the left ear, they attend to all words on that ear, and they are evidently unable to prevent attended irrelevant words from being stored in memory. When the target is expected to be labeled by a physical characteristic (e.g., a distinctive voice quality), the subjects presumably have more confidence in their ability to detect it, and they pay less attention to the irrelevant message in which it is embedded.

SUCCESSFUL DIVISION OF ATTENTION

In contrast to the experiments described in the preceding section, other studies conclusively demonstrate that parallel processing of concurrent verbal stimuli is possible. In an important experiment, Treisman (1970; Treisman & Fearnley, 1971) presented subjects either with single items or with pairs of precisely synchronized auditory items, consisting either of two nonsense syllables or of a nonsense syllable and a digit. The subject was to press a key if one of the items was a digit, and another key if neither item was a digit; his reaction time was measured. On some trials the subject was given advance information about which digit, if any, would be presented. This precuing is known to reduce RT. The experiment was intended to test the hypothesis that concurrent items are processed serially. This hypothesis entails the following sequence of events in response to the dichotic stimuli of the experiment:

(*1*) Determine if the item on one of the ears is a digit.

If it is not—

(2) Switch to the item on the other ear.
(3) Test that item.

When a single stimulus is presented, the process is completed after phase 1. Now consider the effects of precuing. With a single stimulus, precuing abbreviates phase 1. When two stimuli are presented, both phases 1 and 3 will be shortened by precuing. Consequently, the hypothesis of serial processing entails a larger reduction of RT by precuing with pairs than with single stimuli. However, the striking result of this experiment was that precuing reduced RT by 115 milliseconds for both single items and pairs. Evidently, the decision that neither of two simultaneous items is a digit could be made in parallel for the two items.

Although the analysis of precuing effects indicates that processing was parallel, it is important to note that the efficiency of parallel processing was less than the efficiency of processing a single item: RT to pairs was longer by about 80 milliseconds than RT to single stimuli.

Similar results were obtained in a study by Ninio and Kahneman (1973). Subjects were exposed to brief dichotic word lists, and they pressed a key whenever they heard an animal name. Reaction times were measured in two conditions: attention divided between the two ears or focused on one message. Despite the fast presentation rate (two pairs/sec) the subjects detected 77 percent of the targets in the divided attention condition, demonstrating some ability to deal with both messages. A more precise test of filter theory was obtained in that study by comparing the RT distributions in focused and divided attention. According to Broadbent's initial statement, RT in divided attention depends on the setting of the filter at the instant of target presentation: if the filter happens to be selecting the appropriate channel, RT should be short. On the other hand, RT should be long if the filter was set to the wrong channel at the critical instant. Thus, filter theory entails much greater variability of RT in divided attention than in focused attention: the fastest RT's should be identical in both conditions, and there should be very slow RT's in divided attention. Contrary to this prediction, there was little difference in the variability of the two RT-distributions, and the difference between the three fastest reactions in the two conditions (110 msec) was not much less than the difference between the means (140 msec). This pattern of results supports the hypothesis that the processing of simultaneous words is parallel.

Lindsay (1970) has reviewed some studies of psychophysical tasks in which attention was divided among different stimuli and among different relevant aspects of the same stimulus. Subjects in these experiments made absolute judgments of various attributes of simultaneous visual and auditory stimuli. Their performance was evaluated by a measure of information transmission, which reflected their consistency in assigning distinct labels to different stimuli. Subjects transmitted almost as much information on each dimension when they judged both stimuli together as they did when the judgments were made one at a time. Manipulations of stimulus duration had no effect, suggesting that the two discriminations were indeed performed in parallel. Thus, attention was effectively divided between the two tasks (Lindsay, Cuddy & Tulving, 1965; Tulving & Lindsay, 1967), at least when the stimuli to be judged were easily discriminable from one another. Very different results were obtained when discriminability was reduced, and these additional findings will be discussed in the next section.

Evidence of parallel processing was obtained by the present author and his students (Levy, 1971) in studies of recognition memory following dichotic presentation of word lists. The experimental situation has already been mentioned in the discussion of focused attention. In the divided attention condition, the subjects were exposed to dichotic lists of 31 words each, and they subsequently attempted to distinguish words that had been presented from unpresented distractors. The recognition list always included several pairs of items that had been presented simultaneously to the two ears. Filter theory entails a strongly negative relation between the recognition of simultaneous words: if an item on one ear is recognized, then attention must have been directed to that ear at the time of presentation, and therefore away from the other ear. Thus, the probability of recognizing two simultaneous items should be substantially lower than the product of their separate probabilities of recognition.

Several experiments, conducted at various presentation rates on a total of 260 subjects, failed to confirm the prediction from filter theory. The interaction between simultaneous items predicted by this theory simply did not occur. A typical subject in these experiments recognized about 51 percent of right-ear items and 48 percent of left-ear items (equivalent to about 30 percent recognition after correction for chance success), and these values were unaffected by the recognition of the corresponding item on the other ear. In contrast to this independence between simultaneous items, there was a slight but highly consistent negative relation between successive items.

The results indicated that man *can* listen to both ears at once and store some part of what he hears, although recognition performance is far poorer than when he listens to only one ear. The subjects faced with the overwhelming task of listening to two messages at once quickly realized the futility of any active strategy and usually reported adopting a passive, receptive attitude. With this attitude, there were no indications of interference between simultaneous items, but performance on all items was quite poor.

EFFORT AND THE ALLOCATION OF ATTENTION

The evidence of the preceding section is consistent neither with filter theory nor with the Deutsch-Norman theory. Filter theory is invalid because it cannot accommodate the reaction-time evidence which suggests strictly parallel processing. The Deutsch-Norman theory is also incorrect, because it cannot accommodate the effect of channel bias on the detection of a highly significant target item (Treisman & Riley, 1969). Thus, there appears to be more division of attention than filter theory can allow and less than the Deutsch-Norman theory would suggest.

Parallel performance has been evaluated by two main measures: (1) comparisons of the effectiveness of joint performance to effectiveness in a single task; and (2) computations of the correlations between concurrent activities. By both measures, different experimental tasks yield strikingly different results:

(1) Parallel processing of simultaneous inputs sometimes occurs with little interference (e.g., Lindsay, 1970; Lindsay & Norman, 1969). In other situations processing is parallel, but its effectiveness is impaired (Ninio & Kahneman, 1973; Treisman, 1970; Treisman & Fearnley, 1971). Finally, there are cases where parallel processing fails altogether.

(2) The achievements in two concurrent activities are sometimes uncorrelated, although both are impaired (e.g., my own studies of recognition after dichotic listening). In other cases there is a marked negative correlation between the processing of concurrent stimuli, so that successful processing of one makes the response to the other very unlikely (e.g., Moray, 1969b, 1970a, b; Moray & O'Brien, 1967; Shaffer & Hardwick, 1969).

The concept of limited capacity is helpful in ordering these chaotic results. If the effort that man can exert at any time is limited, then any two tasks whose joint demands exceed that limit must be mutually interfering. Thus, the main prediction from an effort theory is that the ability to respond to simultaneous inputs should depend primarily on the demands of the activities among which attention is to be divided.

There is some evidence to confirm this prediction. As was already mentioned, effective parallel processing of stimuli was observed by Lindsay and his associates (Lindsay, 1970). They found that the information conveyed by absolute judgments on a dimension did not decrease markedly when the subject made several judgments on concurrent stimuli, but this pattern held only when the stimuli were highly discriminable. A different result was obtained when the chosen stimuli were less discriminable (Lindsay, Taylor & Forbes, 1968). The total information conveyed in multiple judgments was then rather less than in the single-judgment condition. Thus, ". . . it is not the amount of information in a stimulus, as defined by measures of stimulus uncertainty, but rather the difficulty in discriminating the signal in a given channel that causes performance to break down under multi-channel conditions [Lindsay, 1970, p. 154]."

A series of careful control experiments established that the interference between the simultaneous judgment tasks occurred at the time of stimulus presentation. When a subject was told after the presentation that he was not to report one of the stimuli, his judgments of the other stimuli did not improve. Thus, the interference had already occurred when the irrelevant dimension was indicated. On the other hand, precuing had a positive effect, because it permitted attention to be focused on the appropriate stimulus. The conclusion of this work is that man's capacity to perform concurrent perceptual tasks is limited. Easy tasks can be performed together with little interference, but more difficult tasks cannot.

The capacity model may also explain why the correlation between concurrent activities is nil in recognition, and strongly negative in monitoring, but the interpretation of these results requires further elaboration of the model. The new hypothesis is that an even distribution of attention among concurrent activities is possible only at a low level of total effort. When total effort is high, one of the activities typically draws most of the attention, leaving little for the others. This suggestion is related to the Easterbrook hypothesis discussed in Chapter 3. It implies that attention is divisible at low levels and more nearly unitary at high levels of effort. (See also the discussion of spare capacity on p. 16.)

In the recognition experiments conducted in my laboratory, subjects appear to adopt a passive attitude during the presentation of long (31 words/ear) dichotic lists of words. The phenomenology of the situation is suggestive: subjects report that they deliberately refrain from paying particular attention to any word, because they realize that doing so involves "missing" several other words. Thus, the listener allocates some effort to the processing of both words in a simultaneous pair, but he refrains from checking whether either of the words has been effectively stored in his memory. Under these conditions, recognition performance is poor, but the two items in a pair are prevented from competition or mutual interference.

The situation is quite different in Moray's monitoring experiments (Moray, 1970a, b; Moray & O'Brien, 1967). In the monitoring situation, the activation of a recognition unit corresponding to a target causes a series of changes in the subject's state of attention, as indicated in Figure 8-2. The surge of effort initiated by a tentative recognition is associated with a reduction of the capacity allocated to other signals. The outcome is often failure to perceive another target, rather than a mere delay of response. In discussing a similar monitoring experiment, Shaffer and Hardwick (1969b, p. 403) noted: "It seems that the commitment to translate a signal into a response imposes a further limitation upon, or interferes with, speech recognition." Thus, the even distribution of attention in multiple monitoring represents an unstable equilibrium. An initial tendency to allocate capacity to a target on one channel disrupts that equilibrium, and causes attention to focus on that target.

Whether two targets can be processed at once depends on the amount of effort demanded by the processing. Moray's monitoring task requires an immediate overt response, while our word-recognition task does not. One of my students attempted to find an intermediate level of effort between recognition and monitoring (Avner, 1972). His subjects performed a monitoring task, but they made a covert decision rather than an overt response whenever they detected a critical item. All sub-

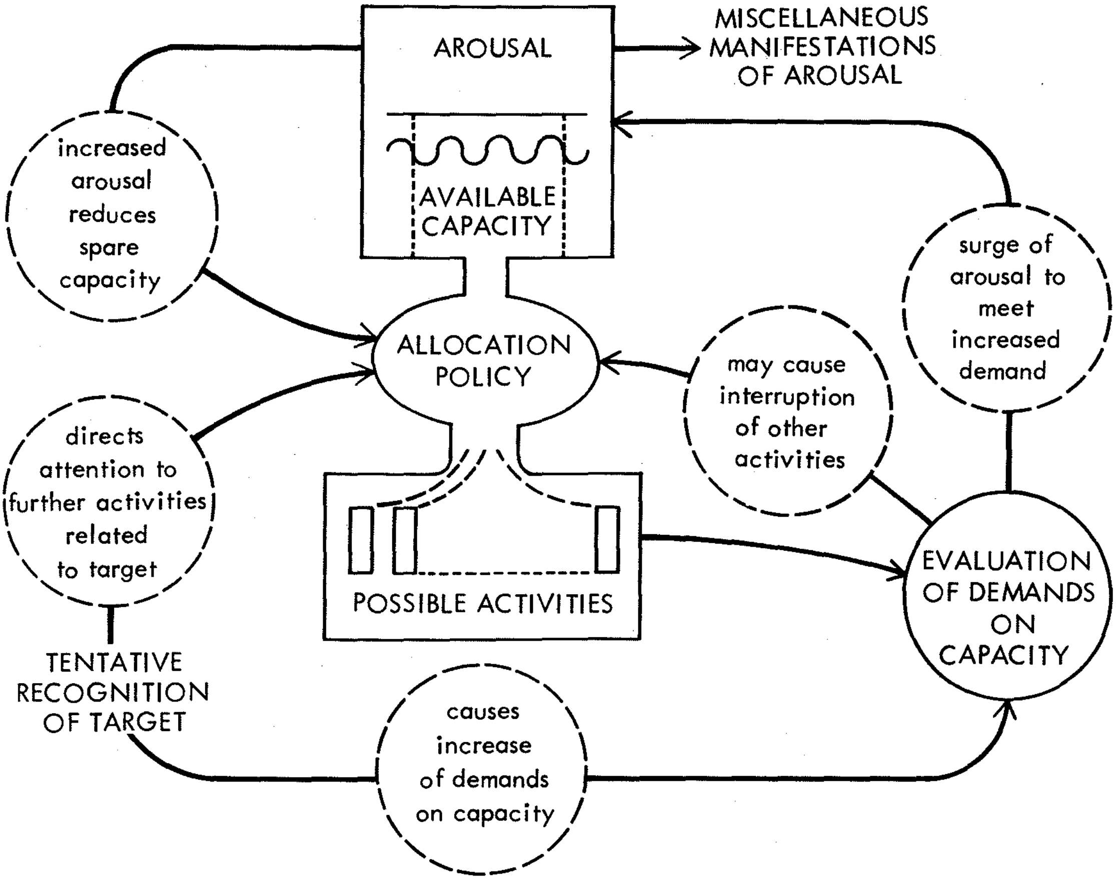

FIGURE 8-2
Effects of the tentative recognition of a target stimulus.

jects listened to 48 five-second dichotic messages (ten unrelated words to each ear) and filled a recognition form where items presented to both ears were to be marked. One group performed only this task. Subjects in two other groups were instructed, in addition, to notice target words which they recalled in writing before the recognition test. In the *content* condition targets were defined by a relevant category (e.g., animal names, capital cities) which was stated before each message. In the *voice* condition, the targets were defined by voice quality (words in a male voice). The number of targets varied from one to three; 16 messages included a pair of simultaneous target items.

There was a marked negative correlation between the recall of such simultaneous targets. Given that one member of the pair had *not* been recalled, the probability that the other member would be recalled was 88 percent in the voice group and 96 percent in the content group. Given that one member of the pair had been recalled, the probability that the other would also be recalled was only 58 percent and 55 percent, respectively for the two groups. The negative correlation between simultaneous targets was pronounced, but it was distinctly lower than in the experiment by Moray and O'Brien (1967), which required an immediate overt response to each target. Thus, Avner appears to have succeeded in producing a situation in which less effort was required than in Moray's tasks, and in which the negative correlation between the responses to simultaneous stimuli was correspondingly less marked.

Avner's subjects detected target items on either ear very effectively. When confronted with simultaneous targets, however, they showed pronounced ear dominance, usually of the right ear. As in the previously described experiment by Colavita (1971) a dominance rule is applied to "break the tie" when two stimuli require a simultaneous response. The dominance effect in Avner's experiment was more prevalent in the voice group than in the content group. In a subsequent study using the same recordings, Gopher (1971) observed that the pattern of ear dominance can be altered by requiring subjects to fixate 20 degrees to the right or to the left of the frontal plane.

Two additional observations of Avner's study are relevant to the interpretation suggested in Figure 8-2. The first concerns the correlation between simultaneous items in recognition. The preceding discussion attributed the independence between simultaneous items in our recognition studies to the subjects' passive attitude. The messages in Avner's study were shorter (ten words per ear, compared to 31 in the other studies), and the subjects appeared to adopt a more active attitude. They also showed a consistent negative correlation between simultaneous items on the recognition test. The results of the experimental and control groups did not differ (the control group performed only the recognition task). The probability (corrected for chance success) that a word would be recognized increased from 40 percent to 50 percent, depending on whether the word with which it was paired was or was not recognized. The negative correlation in recognition, while consistent, was much less pronounced than in recall. This finding is consonant with the view that the negative correlation between concurrent activities is a function of effort.

Another observation concerned the recognition of a non-target word that had been presented simultaneously with a target. The recognition of those words was very severely impaired in the voice group, but there was little or no impairment in the content group. A similar result was obtained by Weg (1971). As may be recalled, Weg instructed subjects to listen to all words on the right ear for a recognition test, and to detect and later recall critical items occasionally presented on the left ear (see p. 143). The recognition of the right-ear word presented simultaneously with a left-ear target was more severely depressed when the target was a digit in a male voice (the rest of the message was in a female voice), than when the target was a digit or an animal name spoken in the same voice as the rest of the message.

The difference between the interfering effects of voice and content targets can be interpreted by noting that a voice target may be "recognized" as a target at an earlier stage of analysis than a content target. Consequently, the narrowing of attention indicated in Figure 8-2 will be more detrimental to the item paired with a voice target, because attention will be withdrawn from it sooner.

In summary, the findings reviewed thus far indicate that parallel processing of simultaneous inputs is possible, contrary to filter theory. There seems to be no single-channel bottleneck in the perceptual system, but attention tends to be more nearly unitary at high levels of effort than when little effort is exerted.

Modality Effects in Divided Attention

Treisman (1969) has offered a theory of divided attention which departs from filter theory in important respects. She proposed that different analyzers can operate in parallel without interference, but that processing within any one analyzer is necessarily serial. This hypothesis explains why responding to the same dimension of various objects is hard, while responding to various features of a single stimulus is easy (see Chap. 6). Another inference from this view is that dividing attention among stimuli in the same modality will be more difficult than when the stimuli are in different modalities: stimuli in any one modality are more likely to reach overlapping analyzers. Indeed, Mowbray (1964) has shown that shadowing a message on one ear is more severely disrupted by the presentation of a single significant word on the other ear than by the visual presentation of a word.

Treisman's argument implied that each analyzer functions as a single channel in which processing is necessarily serial. It also implied that there is only one analyzer for each stimulus feature. This is clearly incorrect: for example, there certainly is spatial duplication of analyzers in the visual system, since we are able to see more than one color and more than one shape at a time. This position was moderated in a subsequent paper by Treisman and Davies (1972): "There may well be some common pool of capacity, perhaps that involved in control processes, but there may also be some more specific limits within the relatively independent perceptual analyzers."

Treisman's theory can best be tested in a monitoring task, where the subject responds to critical targets on several channels. The theory predicts that subjects should be able to monitor two messages as easily as one provided that the messages do not reach the same analyzers. In other words, dividing attention between analyzers should be as effective as focusing attention on one analyzer. On the other hand, dividing attention between messages reaching the same analyzer should be extremely difficult.

Treisman and Davies (1972) tested these predictions. They found that monitoring two auditory or two visual messages was much harder than monitoring messages on different modalities. However, performance in even the easiest condition of divided attention was substantially worse than in focused attention. These results are incompatible with the idea that processing in separate analyzer systems occurs in parallel and without interference. Nevertheless, they indicate an interaction between tasks which departs from a mere summation of effort: tasks involving the same modality become disproportionately more difficult when performed together. Thus, Treisman and Davies have shown that it is particularly difficult to divide attention within a modality, but they did not show that it is easy to divide attention between modalities.

Allport (1971) also reported a study of attention divided among analyzers. He presented three colored outline shapes in which a numeral was sometimes inscribed. The subject was instructed to report the values of the three items on one or two dimensions (color, shape, numeral). Interference occurred when the subject was to report shapes and numerals, but not when he reported color with another dimension. Allport explained this result on the grounds that reading numerals and naming shapes require overlapping analyzers. However, the fact that interference was limited to the second dimension reported suggests that the interference may occur in encoding or in memory rather than in perception, as Allport assumed.

Division of attention within a modality often involves a conflict of orientation tendencies (Kahneman, 1970). In the visual case, for example, it is highly unnatural to "think" about either of two displays without looking at them. Orientation tendencies also arise in audition. Thus, Gopher (1971) has found that the eyes continuously make small sideways excursions during dichotic listening. This elicitation of conflicting orientations may have a detrimental effect on auditory perception. Treisman (1971) observed that shadowing a message which is rapidly alternated between the two ears is more difficult than shadowing a monaural message. A series of studies (Axelrod & Guzy, 1968; Axelrod, Guzy & Diamond, 1968) have shown that the apparent rate of a series of clicks is lower when the clicks are alternated between the two ears than when they are presented to one ear or binaurally. Axelrod and Powazek (1972) showed that the apparent click-rate increases as the spatial separation between the sources is reduced, and they pointed out that this result could be due to the elicitation of motor response tendencies.

When the stimuli to be attended are in different modalities, however, orienting appropriately is not difficult. Imagine trying to listen to a message to your right ear while looking to your left. You will probably notice a tendency to cock your head toward your right shoulder.

Dividing attention within a modality is also difficult whenever a task involves storage. Kroll *et al.* (1970) have found that a single target word presented during shadowing is retained better if it is visual than if it is included within the auditory message. The visual item appears to be relatively immune to retroactive interference from the shadowing task. This observation suggests that visual and auditory storage mechanisms are at least partly independent. Consequently, interference is more likely to arise between items presented to the same modality than between items on different modalities (Parkinson, 1972). Related results were reported by Treisman and Davies (1972, exp. 1) in a bisensory split-span experiment. The usual memory loss for the second series was avoided if that series was presented on a different modality, and if different modes of response were employed for the series. Response mode plays an important role in this context, and it is discussed in greater detail in Chapter 10.

REVIEW

This chapter began with the question of whether simultaneous inputs are processed in parallel or in sequence. The conclusion is that both modes of processing occur, depending on the task and on the circumstances. Several experimental designs have been used to study this question.

Split-span. Subjects tend to group their responses in accordance with the perceived grouping of stimuli. In general, this strategy yields grouping by channel in the dichotic case, or by modality in the bisensory case. However, if grouping by ear yields an uncomfortable response sequence (e.g., a medley of digits and letters in each group), grouping by type can be adopted.

Monitoring several channels is possible, but less effective than monitoring a single channel. Reaction-time evidence suggests that analysis of concurrent signals occurs in parallel, but at a slower rate than in focused attention. It appears to be especially difficult to monitor spatially separated messages in the same modality, perhaps because conflicting orientation tendencies are elicited. Special attention to one channel makes a significant target on another channel difficult to detect, contrary to the Deutsch-Norman theory.

Responses to simultaneous items frequently fail. The subject almost always responds to one of the stimuli but often remains unaware of the other, producing a negative correlation between the occurrence of the two responses. "Tie-breaking" rules are consistently applied in such cases, including dominance of a light over a tone, or of a word presented to the right ear over a word to the left ear. The negative correlation between responses to simultaneous stimuli is reduced when the responses are made less demanding. This result supports an effort theory of divided attention. In addition, there is a modality effect, such that simultaneous targets on the same modality are more difficult to detect and to process than simultaneous targets on different modalities.

9

Speeded Responses to Simultaneous and to Immediately Successive Signals

Measures of reaction time have been used extensively in attempts to study man's ability to divide his attention between two response tasks which overlap in time. The first section of this chapter discusses the issue of response integrality: when are two physically distinct responses properly viewed as components of a single molar response? Subsequent sections deal with results obtained with quickly successive signals. Additional studies in which reaction time is used to measure the division of attention are described in Chapter 10.

MULTIPLE RESPONSES AND MULTIPLE TASKS

How does man produce multiple responses to multiple simultaneous or immediately successive signals? A vast number of studies have been devoted to this question, in an attempt to clarify the interactions between concurrent processes of perception, decision, and response. A preliminary question that must be answered, however, concerns the very definition of multiple signals and multiple responses. The discussion of integrality in Chapter 6, and of grouping processes in Chapters 5 and 7, made it clear that the question of what constitutes a single stimulus is an empirical one. The mere fact that the experimenter can independently manipulate some physical dimensions of objects does not guarantee that these dimensions function as separate stimuli in the control of the subject's behavior. Similarly, the fact that the components of a complex response can be measured separately does not guarantee that it is useful to view the performance of each of these components as a separate activity. It must be admitted, however, that our understanding of integrality and grouping of responses lags far behind our understanding of integrality and grouping of percepts.

Consider, for example, an experiment in which the subject presses a key with his right index finger when he hears a tone and another key with his left index finger when a light is flashed. The unexpected presentation of a light and a tone at the same time leads to an either-or choice, which typically favors the response to the light (Colavita, 1971). With proper instructions, however, a subject will easily learn to treat the joint occurrence of a light and a tone as a single event, to which he will respond by pressing both keys. The physically separate responses of the two fingers, which constitute alternative acts in Colavita's experiment, can readily be combined into a molar response unit.

The nature of the effective response unit is not always so easy to discern. As an example of this problem, we shall consider in detail a careful study by Schvaneveldt (1969, exp. 2). The experiment was conducted as follows: the subject was seated facing four display units and four response buttons. On a trial, a single numeral was shown in one of the units. The subject responded by pressing the corresponding button (the manual task) and by saying a letter corresponding to the numeral: A for 1, B for 2, C for 3, and D for 4 (the verbal task). The information associated with each of the tasks was varied in a series of experimental conditions. In the simplest condition (0 bits of information for both the manual and the verbal tasks), the numeral "1" was shown on every trial, always in the same display unit. Whenever the stimulus was shown, the subject pressed a button with the same finger and said "A," as fast as he could. In the most complex condition (2 bits of information for both the manual and the verbal tasks), any one of the four numerals could appear in any one of the four units. The information of both tasks was varied in a complete factorial design, with three levels of uncertainty (0, 1, 2 bits) represented for each task. The subjects also performed in single-task conditions, where only one response (verbal or manual) was required. Unfortunately, the single-task conditions were always tested early in practice and cannot be compared unequivocally with the double-task conditions.

Schvaneveldt compared the observed latencies of manual and verbal responses to two theoretical models: (1) An *independence* model, according to which the latency of the verbal and the manual responses should depend only on the number of choices available for each of these responses. In this model, the reaction time for a response should be the same, regardless of whether that response is performed singly or in conjunction with another response. (2) A *single-channel* or successiveness model, according to which the two responses can only be performed in strict succession. In this model, the latency of the slower of the two responses in each double-task condition should equal the sum of the latencies of both responses in the corresponding single-task conditions.

Both models failed. The latency of each response was found to depend on the complexity of the other, contrary to the independence model, and the latency of the slower response was far shorter than the sum of single latencies, contrary to the successiveness model. Part of the data were displayed in the manner of Figure 9-1. This figure indicates an interaction: the verbal latency increases with the information of the verbal task, but the rate of increase depends on the complexity of the manual task. Specifically, the number of choices in the verbal response has relatively little effect on RT when the manual response also involves a choice. Schvaneveldt (1969, p. 296) concluded: "The interesting result . . . is the suggestion of increasing overlap between two tasks as the uncertainty in the tasks is increased." It seems natural to infer from these results that the decision processes involved in the two tasks can occur in parallel with little or no interference (Keele, 1973).

A different approach to the same results is possible, if one rejects the basic assumption that the two responses correspond to distinct tasks that the subject performs in parallel. Let us consider the alternative possibility that the verbal and manual responses are components of a molar response unit, much as the distinct movements of hand and foot are components of the act of switching gears while driving and automobile. In this view, the subject makes a single decision on each trial "press-this-button-and-say-that-letter." Note that this hypothesis does not entail that the responses should occur in precise synchrony, since they involve different muscle groups. If each molar response is controlled by a single decision process, however, the latencies of both components should vary in unison with the latency of the decision. Thus, the interval between the two responses (IRI) should remain about the same under all conditions. In contrast, an independence model in which the latencies of the component responses are the same in single-task and dual-task conditions, entails large variations of IRI across conditions: from +328 milliseconds (where the verbal response involves a 2-bit decision and the manual response is simple) to −163 milliseconds (where the verbal response is simple and the manual is complex).

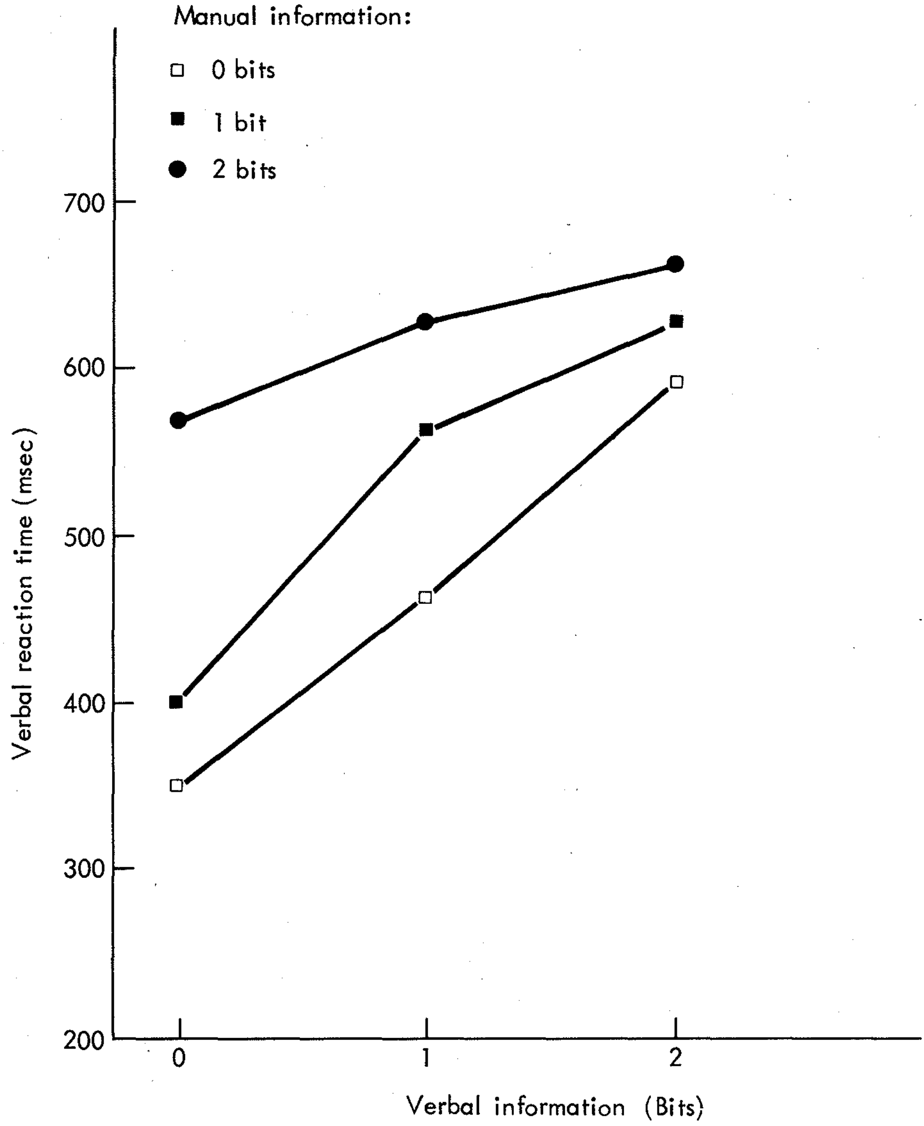

FIGURE 9-1
Verbal RT as a function of information in verbal response, for three levels of information in manual response (from Schvaneveldt, 1969, with permission).

Another implication of the response-grouping hypothesis is that the latency of the compound decision should depend on the overall complexity of that decision, i.e., on the total number of different response patterns among which the subject is required to choose. For example, the latencies of both the verbal and the manual responses should be about the same in the three experimental conditions that require a choice among four alternative compound responses, namely the conditions in which: (1) the verbal and the manual responses each involve a choice between two alternatives; (2) the verbal response is a four-alternative choice and the manual response is simple; (3) the verbal response is simple and the manual response is a four-alternative choice.

The data relevant to these predictions are shown in Figure 9-2, which presents the average RT of the manual and verbal responses in the nine conditions of Schvaneveldt's experiment. The grouping hypothesis fares rather well. The verbal response is consistently slower than the manual, regardless of the complexity of the choice associated with each of these responses. Furthermore, the latencies of the responses are clearly dependent on the overall complexity of the compound choice. Note that the verbal latencies recorded in Figure 9-2 are the same data that were presented in Figure 9-1. What appeared to be an interaction in the former display now appears as a nonlinear trend relating verbal RT to total information.

While the major predictions of the grouping hypothesis are con-

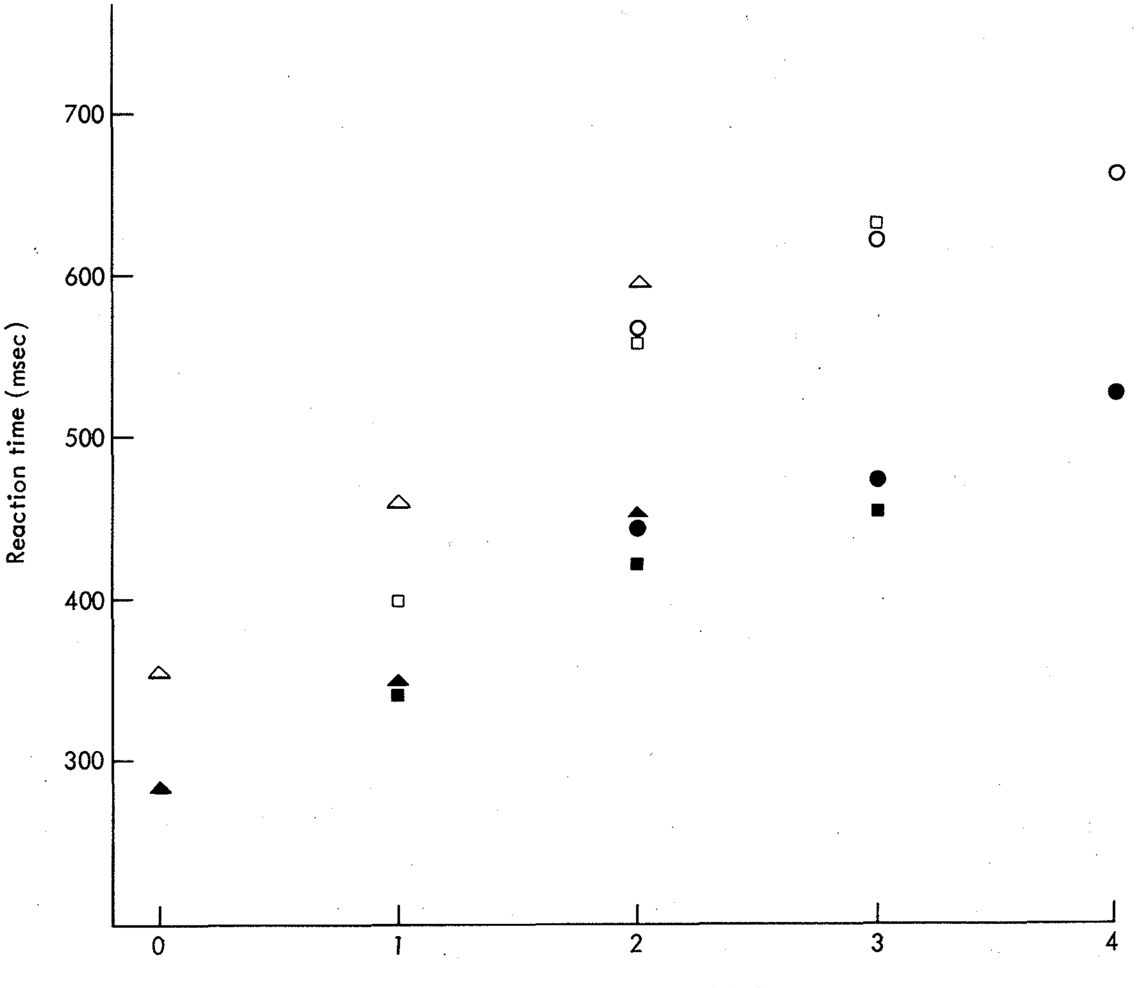

FIGURE 9-2
Manual RT (filled symbols) and verbal RT (unfilled symbols) as a function of total information. Symbols identify the information in the manual response: 0 bits (triangles); 1 bit (squares); 2 bits (circles).

firmed, there is a trend in Figure 9-2 that this hypothesis does not predict: the IRI between the two responses tends to increase with the complexity of the task. It appears that the organization of the compound response becomes looser at a high level of complexity. Why this occurs is not clear. Certainly, however, the implication of this result is that there is *less* overlap between the processes leading to the two responses when the situation is complex than when it is simple. This conclusion is diametrically opposite to the conclusion that Schvaneveldt drew from consideration of the data of Figure 9-1.

The preceding discussion shows that the question of whether two distinct responses constitute two tasks or one, cannot be dismissed as a matter of definition. It is an empirical question. Integrality of responses has observable consequences, and response units must be discovered, not defined. In Schvaneveldt's study, there were two indications that response grouping or integration occurred. First, the latency of the manual response, which was always the first to occur, depended equally on the information conveyed by both the position and the identity of the numeral. Second, the IRI between the two responses was relatively short and varied only within narrow limits. However, the fact that IRI did vary systematically with the overall complexity of the task suggests that response integration may be a matter of degree.

Phenomena of grouping and organization are as important in the context of response as they are in the context of perception. Response grouping and integration extend over both space and time: complex coordinated acts such as shifting gears in an automobile involve different limbs and a relatively prolonged sequence of subordinate activities. As is also true of perceptual organization, response organization is hierarchical, and response units are integrated in groups of increasing size. It is often easy to discover the size of the dominant unit of organization. Speak aloud, for example, and try to obey the instruction "say everything twice." What did you discover? What was the size of the units that you chose to repeat? Almost invariably the repeated unit consists of more than one word, though the words are clearly present as distinct subordinate units. The effect is not restricted to verbal response. Set yourself to make free-form movements with both hands. Now try to "do everything twice." The analogy of the motor experience to the verbal will be clearly evident.

The isolation of valid response units is an essential prerequisite to the study of divided attention in motor performance. It is only meaningful to speak of attention as divided among isolable processes, but these isolable processes must first be discovered (Posner, Lewis & Conrad, 1972). The discussion of perceptual attention in earlier chapters led us to reject the concept of channel and to be highly skeptical of the psychological validity of arbitrarily defined dimensions. The analysis of Schvaneveldt's experiment suggests that we must be equally skeptical of arbitrarily defined response units.

The discussion of perceptual units in an earlier chapter suggested that the rules of grouping are relatively impervious to learning. Response units, on the other hand, are often fashioned in prolonged experience. The acquisition of complex skills consists in large part of the formation of extended units. An impressive example of this process was described by Seibel (1963). He employed a display of ten bulbs, any of which was equally likely to be illuminated or left dark on each trial. The subjects responded to the pattern of lights by pressing corresponding keys with the fingers of both hands. After extremely prolonged practice (75,000 trials!), RT no longer depended on the number of keys that were pressed, or on the size of the ensemble of possible patterns. Apparently, the pattern of lights was perceived as a unit and elicited a unitary, integrated response.

In many situations, response integration does not take place. When the stimuli are not expected to occur together, the responses to them will tend to be successive (Dimond, 1971), or only one response will occur (Avner, 1972; Colavita, 1971; Moray, 1970a, b; Moray & O'Brien, 1967). Finally, response grouping can be prevented when the two stimuli are separated in time. Subjects can obey the instruction to respond to the first stimulus without waiting for the second, even if the interval between the two stimuli is as brief as 50–100 milliseconds (Sanders & Keuss, 1969). In that case, the response to the second stimulus is often delayed. The next sections review some of the research conducted in this paradigm.

INTER-RESPONSE INTERVAL AND THE PSYCHOLOGICAL REFRACTORY PERIOD

A vast amount of research has been devoted to the question of how attention is allocated when two distinct stimuli demand responses in very rapid succession. Craik (1947, 1948) is usually credited with the main discoveries and the first theoretical formulation in this area. He studied a tracking task in which the target followed a course that jumped from one level to another at variable intervals (Vince, 1948). The basic finding was that, whenever two signals followed one another within 0.5 seconds, the reaction to the second signal was markedly delayed. The interval between the two signals was the only effective variable; the magnitude of the second signal did not seem to matter. This result led Craik to describe the intermittence of corrective processes by the term "psychological refractory period" (PRP) which had been introduced earlier (Telford, 1931). Craik suggested that man behaves as an intermittent servomechanism; the main characteristic of such a mechanism is that the corrections it makes when performing a continuous action are discrete, and limited in rate. Information that arrives during the refractory period which follows each correction is acted upon only at the next instant of sampling.

Subsequent investigations of refractoriness have largely abandoned the tracking task in favor of the simpler situation in which the subject reacts to two rapidly successive stimuli, S_1 and S_2. The sequence of events in a typical trial is shown in Figure 9-3. The question that is raised in such experiments is whether the subject can prepare the response (R_2) to the second stimulus (S_2) while engaged in preparing or executing the response (R_1) to the first stimulus (S_1).

The data of a reaction-time experiment in the refractoriness paradigm are usually plotted as in Figure 9-4, in which RT_2 is plotted as a function of the interval (ISI) between S_1 and S_2. Figure 9-4 presents theoretical functions for the dependence of RT_2 on ISI, which are derived from the *single-channel hypothesis,* as formulated by Welford (1952, 1959, 1967) and by Davis (1957). This hypothesis is an application of Craik's original view to the reaction-time situation. The main assumption of single-channel theory is that the response-selection stage of information-processing is a bottleneck, or single channel, which can select responses only one at a time. The one exception that Welford admitted

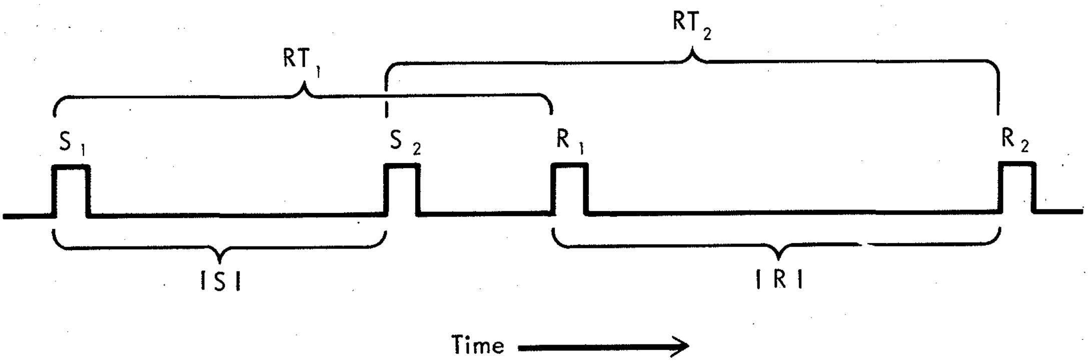

FIGURE 9-3
The sequence of events in a typical trial of a refractoriness study: S_1 and S_2 are successive stimuli; R_1 and R_2 are the corresponding responses.

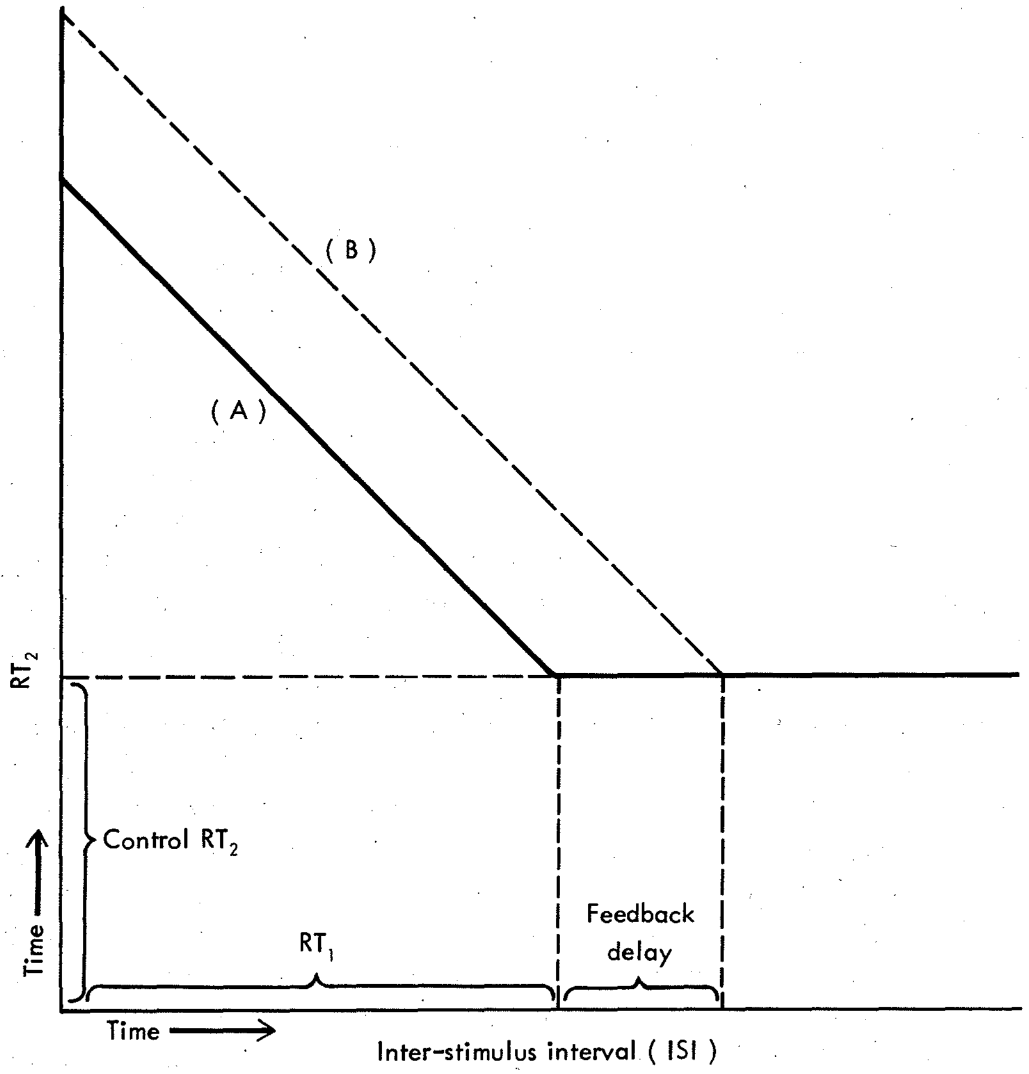

FIGURE 9-4
Reaction time of second response (RT$_2$) plotted as a function of inter-stimulus interval (ISI). Two predictions from single-channel theory are shown: (A) prediction on the assumption that the processing of S$_2$ begins with the execution of R$_1$; (B) prediction on the assumption of a further delay for processing feedback.

was the occurrence of response grouping when S$_1$ and S$_2$ are nearly simultaneous.

The simplest version of the single-channel hypothesis asserts that the decision-mechanism becomes available to prepare the second response only after the first response is made. This prediction is labeled A in Figure 9-4. When S$_2$ is shown before R$_1$ occurs, it is held in storage, and processing of S$_2$ begins only with the occurrence of R$_1$. In this view, a stimulus S$_2$ that preceded R$_1$ is treated as if it had in fact been simultaneous with R$_1$. Accordingly, RT$_2$ should be normal for all S$_2$ that occur after R$_1$, and it should be delayed for all S$_2$ that precede R$_1$. The function shown in Figure 9-4 is idealized; in actual data, the variability of RT_1 would be expected to cause a smooth transition between the two arms of the RT function (Bertelson, 1967; Welford, 1968).

In many experiments RT_2 is longer than normal even when S_2 is presented after the occurrence of R_1. Davis (1957) attempted to explain these additional delays by postulating an additional central refractory state which lasts about 100 milliseconds. Welford (1952, 1959, 1967) proposed that the system may be occupied for some time by feedback from the first response, and he also advanced the interesting suggestion that waiting for feedback from R_1 is optional: it is most likely to occur when the execution of R_1 demands a high degree of precision, or in early stages of practice. The prediction from single-channel theory which incorporates the additional assumption of post-response delay is labeled B in Figure 9-4.

Single-channel theory asserts that division of attention between response processes is impossible. This is a surprising contention, in view of the vast amount of evidence indicating that attention is often divisible. Indeed, there are very few experimental reports in which the data fit the theoretical predictions that were illustrated in Figure 9-4; in most studies the discrepancies between observations and predictions are large and systematic. Nevertheless, single-channel theory has often been viewed as the dominant theory in this area (Bertelson, 1966; Smith, 1967b).

The survival of single-channel theory in the face of massive contradictory evidence can be traced, at least in part, to the tradition of plotting experimental results in the manner of Figure 9-4, where RT_2 is shown as a function of ISI. It is equally reasonable, however, to formulate the experimental question as follows: How does the interval between the two *responses* R_1 and R_2 (IRI) vary with the interval between the two *stimuli,* S_1 and S_2?

This formulation suggests that experimental data should be displayed as in Figure 9-5, which again presents two alternative predictions from single-channel theory. According to that theory, IRI should be constant up to a value of ISI which is equal to R_1 (version A) or larger (version B). Beyond that point, IRI should rise directly with ISI. Note that a constant IRI is predicted by two very different hypotheses: response grouping and single-channel operation. However, the single-channel hypothesis also entails that IRI should be relatively long, and that the latency of R_1 should be independent of the complexity of the subsequent response, R_2. As was shown in the preceding section, the grouping hypothesis entails that RT_1 and RT_2 should vary in unison whenever the complexity of either component of the task is altered.

As an illustration of the two modes of analysis of refractoriness data, consider an experiment by Smith (1969), in which the subject was

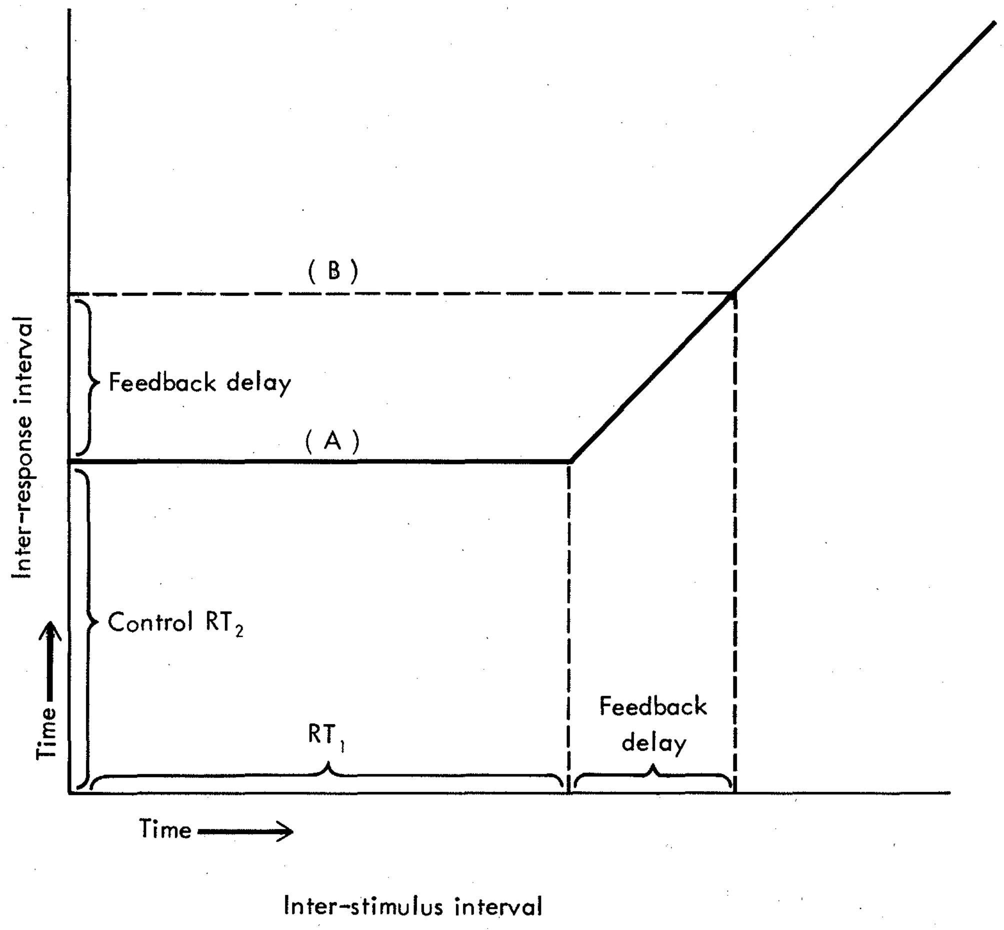

FIGURE 9-5
Inter-response interval as a function of inter-stimulus interval. The predictions from single-channel theory correspond to the functions labeled (A) and (B) in Figure 9-4.

required to make two choice-responses in quick succession. The second response (R_2) was always a two-alternative choice. The experimental conditions varied in the complexity of the first response (R_1). The three conditions studied were 2-2, 4-2, and 8-2, where the two numbers in each pair refer to the number of alternatives for R_1 and R_2 respectively.

Figure 9-6 presents the main results of this experiment, analyzed and plotted in terms of RT_2 (panel A) or IRI (panel B). The two panels respectively correspond to the graphical representations introduced in Figures 9-4 and 9-5. The data of panel A appear at first glance to correspond quite well to the predictions from single-channel theory, and they were interpreted as supporting that theory (Smith, 1969).

To draw the results in panel B, IRI was computed for each data point separately, because RT_1 varied slightly as a function of ISI and of the complexity of R_2. The equation for the computation is:

$$\mathrm{IRI} = \mathrm{RT}_2 + \mathrm{ISI} - \mathrm{RT}_1 \text{ (see Fig. 9-3).}$$

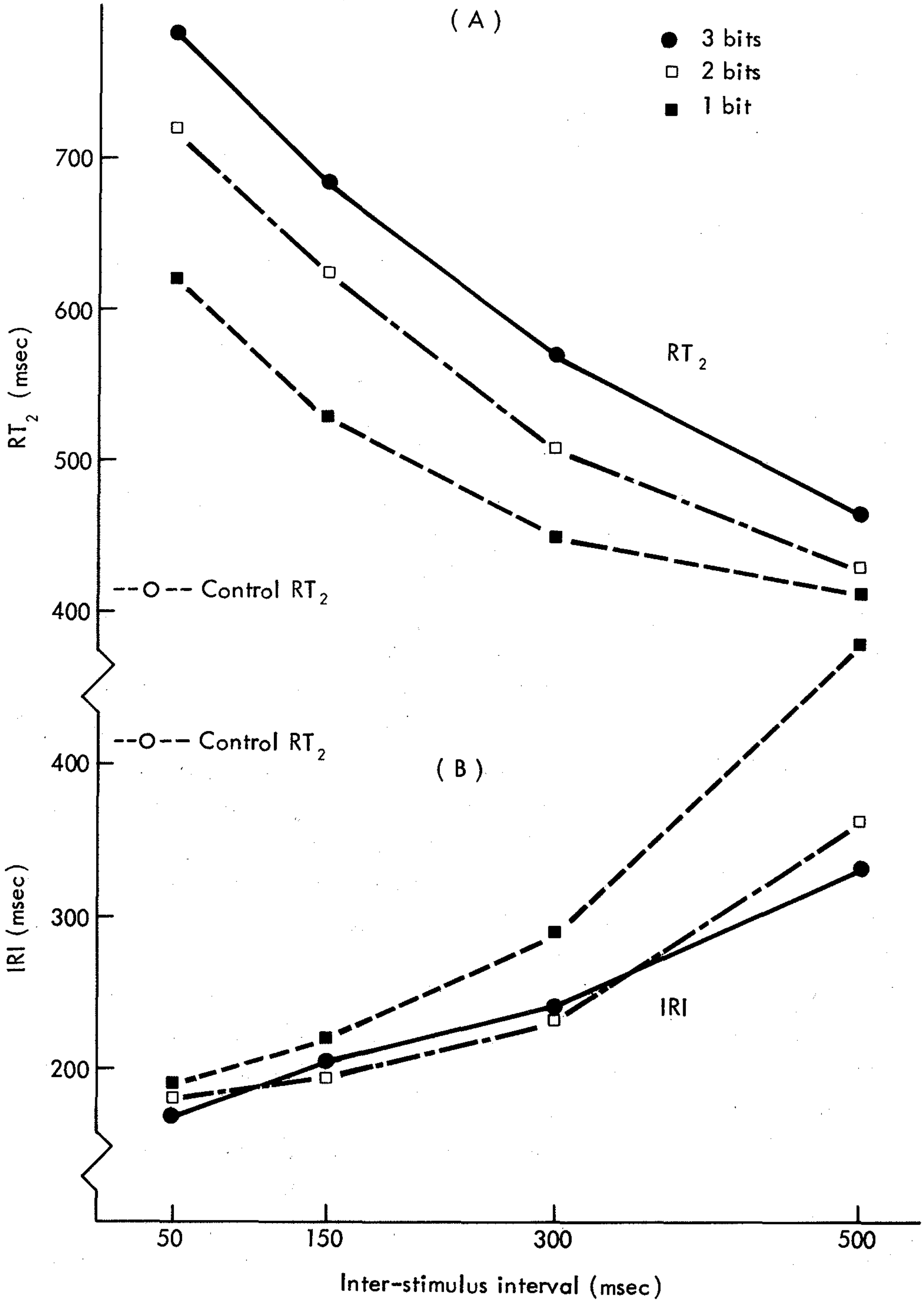

FIGURE 9-6
Data from Smith (*Acta Psychologica, 30,* 1969). RT_2 and IRI are shown as a function of ISI. The parameter is the information of R_1.

As plotted in Figure 9-6, panel B, the data are seen to violate drastically the predictions of single-channel theory, since the horizontal segment predicted by that theory is missing in all cases. The discrepancy between the impressions that are gained from observing the two panels of Figure 9-6 is due to a simple fact of sensory discrimination: we are much more sensitive to deviations of a line from the horizontal than to deviations from a slope of minus one!

The results of Figure 9-6 are incompatible with single-channel theory for two reasons: (1) because they indicate that IRI can be shorter than the control value of RT_2, so that some processing must be parallel; (2) because the slope of the functions that relate IRI to ISI is always positive, again indicating parallel processing. These deviations from single-channel predictions are much too large to be explained by random fluctuations of RT_1.

The slope of the function that relates IRI to ISI in Figure 9-6, panel B, is a meaningful parameter: it represents the amount by which IRI may be shortened (in msec) if the presentation of S_2 is advanced by one millisecond. Both single-channel theory and a grouping hypothesis entail a slope of zero for the range of short ISI's. On the other hand, the hypothesis that the processes leading to the two responses are completely independent entails that the slope of the function should be unity. The result shown in Figure 9-6B is typical: the slope of the IRI function is positive throughout, and the function is positively accelerated. This result is incompatible with the three hypotheses that have been introduced in this discussion: single-channel theory, and the grouping and independence models. The results imply that some attention is devoted to the processing of S_2-R_2 as soon as S_2 is presented. Furthermore, the amount of attention devoted to S_2 increases steadily during the latency of R_1. These results are typical of a large number of studies of refractoriness (e.g., Bertelson, 1967; Broadbent & Gregory, 1967, exp. 1; Nickerson, 1967; Sanders & Keuss, 1969).

It may be noted in Figure 9-6 that the slope of the IRI function varies inversely with the complexity of R_1: IRI increases more slowly with ISI when R_1 is complex than when it is simple. Since the slope of the IRI function reflects the rate at which S_2 is processed, this finding appears to support an effort theory, which entails a reduced sharing of capacity when one of the two competing activities is highly demanding. However, a more fundamental observation is that the shortest IRI is almost the same at the three levels of complexity. This result suggests a modified concept of refractoriness, i.e., that there is a minimal interval that separates successive responses when these responses are not grouped. If such a minimal IRI is a basic feature of the system, the divergence of the curves follows necessarily, as the following argument shows. At a low value of ISI, both RT_1 and RT_2 are affected by a change in the complexity of R_1, but IRI is the same for different levels of complexity. At a high value of ISI, on the other hand, only RT_1 is affected by the complexity of R_1 and IRI is consequently longer when R_1 is simple then when it is complex. Between the two values of ISI, therefore, the slope of the IRI function must be generally steeper for the simpler R_1. Since this result follows necessarily from the assumption of a common minimal value of IRI, the temptation to interpret the differences between the slopes of the curves must be firmly resisted.

There is additional evidence for the notion of a minimal IRI between ungrouped responses. Karlin and Kestenbaum (1968) carried out an experiment very similar to that of Smith (1969). They studied five different combinations of RT tasks. In the notation introduced earlier, the tasks were: 1-2; 2-2; 5-2; 1-1; 2-1. The minimal values of IRI were almost the same for all conditions: they varied only from 220 milliseconds (for the 1-2 condition) to 244 milliseconds (for the 2-1 condition). The data were generally very similar to those shown in Figure 9-6: the slope of the IRI function was positive in all conditions and at all values of ISI, and the curves diverged systematically as a function of R_1 complexity. The complexity of R_2, on the other hand, had very little effect on the IRI functions.

Keele (1973) has emphasized the importance of these observations by Karlin and Kestenbaum, and he made them the cornerstone of a general view of attention. Although he did not analyze the data in terms of IRI, it is probably easiest to present his approach in such terms. In his view, the finding that the minimal IRI does not vary greatly with the complexity of responses indicates that the processes leading to the two responses interact only at the stage of response initiation, while earlier operations occur in parallel and without interference. Thus, Keele separated the stages of information-processing into two sets: (1) perceptual analysis and memory retrieval (including response selection); (2) initiation and execution of responses. He suggested that the earlier operations occur in parallel and without interference because they require no attention. Only response-related operations, such as rehearsal or the initiation of overt responses, demand attention and are mutually interfering. The constancy of the minimal IRI with variations of response complexity is consistent with this hypothesis of a conflict at the stage of response initiation.

Keele's position that the processes of perception and retrieval do not depend on attention is similar to the views of Deutsch and Deutsch (1963) and Norman (1968), which were found inadequate in preceding chapters. However, the finding which Keele emphasizes, i.e., the near constancy of minimal IRI over experimental conditions, does appear to be of fundamental importance. Perhaps this was the kernel of truth in the original hypothesis of psychological refractoriness. If the minimal IRI is independent of response complexity, the single channel cannot be located at the stage of response selection, as classical single-channel theory would have it. It must be a feature of response organization. Unfortunately, however, there is not enough information concerning the generality of this effect. There appear to be conditions where responses to independent stimuli, apparently ungrouped, nevertheless occur in very close succession (Posner, personal communication). There is a basic, unsolved problem here.

While this section ends on a note of doubt, it may be useful to review its more positive conclusions. It was suggested that a more incisive analysis of the refractoriness paradigm is possible when IRI, rather than RT_2, is adopted as the basic dependent variable. Two parameters of the IRI function were isolated: the minimum value of IRI (typically observed when ISI is very short) and the general slope of the function. The slope is positive in most studies of refractoriness, but it is almost always less than one. This finding is incompatible with the hypotheses of strict successiveness (single-channel), independence and grouping. Thus, while there must be substantial temporal overlap between the processes elicited by S_1 and S_2, these processes do interact. Another finding is that the shortest IRI is sometimes approximately constant in different experimental conditions. This result is compatible with the existence of a state of motor refractoriness following R_1. Keele has inferred the more radical conclusion that competition occurs only at the stage of response initiation, but the next section will present some evidence against this hypothesis.

REFRACTORINESS AND EFFORT

The main conclusion of the preceding section was that subjects in the refractoriness paradigm usually allocate some capacity to S_2 as soon as it is shown, well before R_1 is completed. This is contrary to any single-channel theory. In isolated cases, however, the predictions of single-channel theory are quite strictly upheld. It is therefore of interest to isolate the conditions under which this finding is obtained.

Figure 9-7 is redrawn from a study by Broadbent and Gregory (1967). In that experiment, the subject was first shown one of two lights on one side, to which he responded by depressing one of two keys. He was then shown one of two lights on his other side, to which he responded with the other hand. The instructions and the knowledge of results given after each trial defined the response to the first of the two signals as the primary task. Two different conditions are shown in the figure. In one (broken line), the responses to the lights were compatible

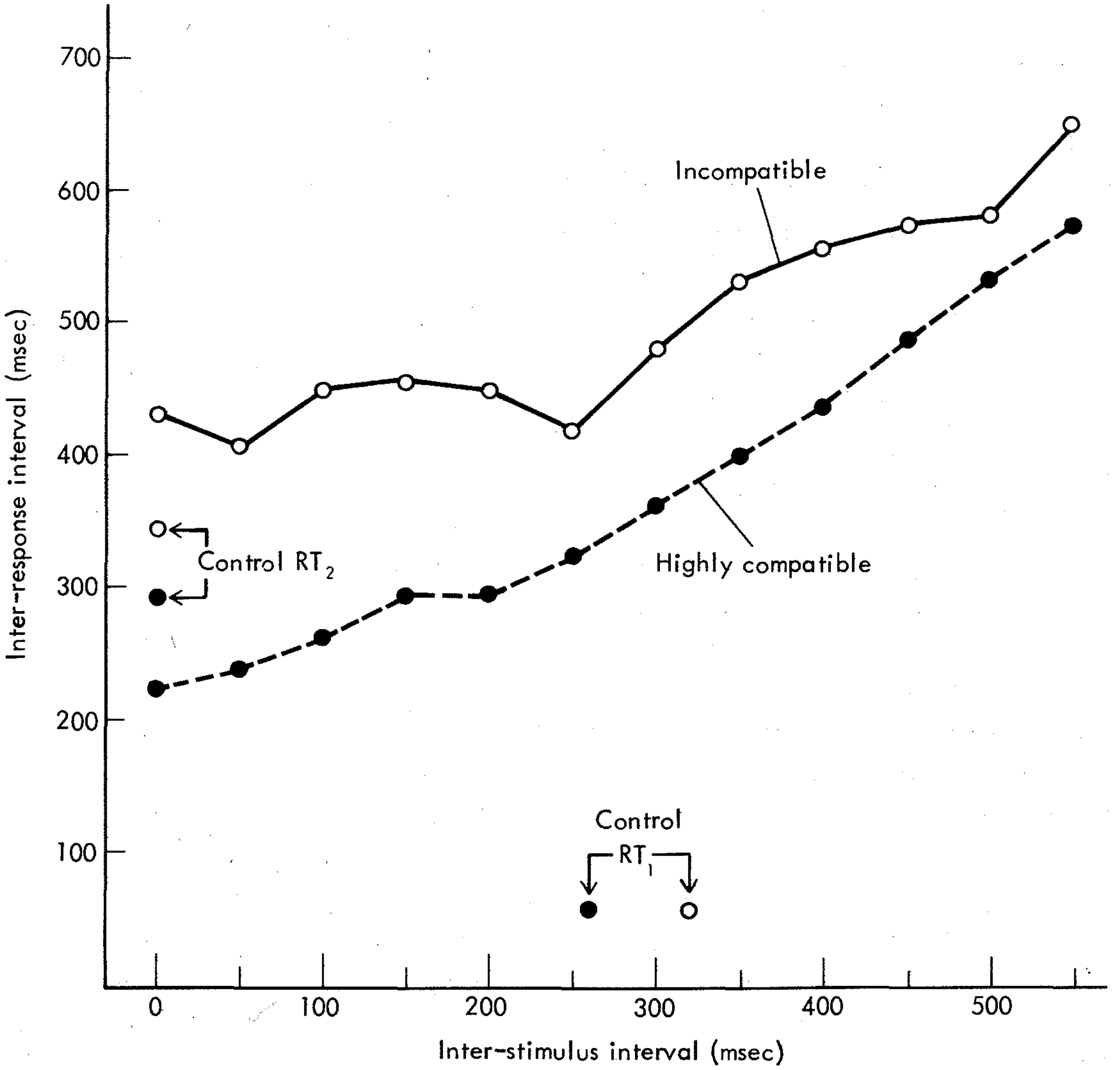

FIGURE 9-7
Data from Broadbent and Gregory (1967), with permission of The Royal Society.

with the stimuli: the subject pressed the key located under each light that was flashed. In the other condition (solid line), the S-R relations were incompatible in both R_1 and R_2 because the subject was required to press the key under the light that was *not* flashed in each pair.

The results in the two conditions are markedly different. When the two reactions are compatible, there is considerable parallel processing, as indicated by low values of IRI and by the fact that the slope of the IRI function is consistently positive. When the reactions are incompatible, in contrast, there is no evidence of any sharing of capacity during the first 250 milliseconds of exposure. In addition, the processing of the second reaction is relatively ineffective even after R_1 is completed, as indicated by the fact that the IRI function is of less than unit slope. The shortest IRI in that condition is substantially longer than the control value of RT_2, indicating a prolonged disruption of the second reaction by the occurrence of the first.

These results are not consistent with the theory proposed by Keele (1973). If the processes that precede response initiation require no attention and occur in parallel, there is no special reason for a variation of stimulus-response compatibility to affect the IRI function. The locus of difficulty in an incompatible situation is in the stages of retrieval and selection of the appropriate response, which Keele assumed to be non-attentive. At the stages of initiation and execution, compatibility should have no further effects. Thus, Keele's theory lacks a mechanism that would explain the effect of compatibility on the minimal value of IRI and on the slope of the function.

The qualitative difference between the two IRI functions of Figure 9-7 suggests a far-reaching conclusion: perhaps no model can be correct which assumes that the processing of S_1 and S_2 is necessarily parallel, nor can a model be correct which assumes that processing of such stimuli is necessarily serial. Models that assume a consistent mode of operation under all conditions may be termed "hardware" models. They attempt to explain the results in terms of the structure of the machine. However, the machine seems to be able to organize its operation in different ways. Thus the device with which we are concerned is capable of purely serial processing on some occasions, and of parallel processing on others. The behavior of such a device in any situation is perhaps better explained by reference to the program which governs its operation than by assuming that its function necessarily mirrors its structure. This is not to deny that structural limitations exist, but merely to state the obvious point that the observation that a system behaves in a certain manner does not imply that the system must behave in that manner. When the operation of the system is shown to be qualitatively different in different conditions, its behavior in any one condition is best explained in terms of software, program, or strategy. The use of the concept of allocation policy in the present work is intended to suggest such an approach to attention. In Chapters 7 and 8, it was shown that man can both focus and divide his attention, within certain limitations that depend on the task and on the circumstances. It should not be surprising to observe a similar flexibility in the allocation of capacity in the context of successive speeded responses.

A study in the refractoriness paradigm carried out in my laboratory (Kafry, 1971) led to the fortuitous discovery of another case in which a slight modification of experimental conditions causes a qualitative alteration in the allocation of capacity. Kafry investigated refractoriness in the RSI case, i.e., the experimental situation in which S_2 is always presented some time *after* the occurrence of R_1 (Rabbitt, 1969; Triggs, 1968). She was looking for possible refractoriness effects following a response (Davis, 1957; Welford, 1959).

In all the experiments in her study, R_2 was a compatible three-choice response to one of three lights, executed with the right hand. In the two conditions shown in Figure 9-8, the subject's first task (R_1) was to stop a digital millisecond counter as close as possible to a specified value (600 or 1200 msec in these data). The counter started at zero on each trial, and the subject stopped it by depressing a key with his left hand. The key-press caused S_2 to appear, either immediately (RSI = 0) or after a variable delay. Figure 9-8 includes data for two groups of subjects who differ markedly, on the average, in psychomotor skills: 20 undergraduates and 20 flight cadets.

The results for both groups were very similar: the "600" condition caused total refractoriness for about 200 milliseconds following the

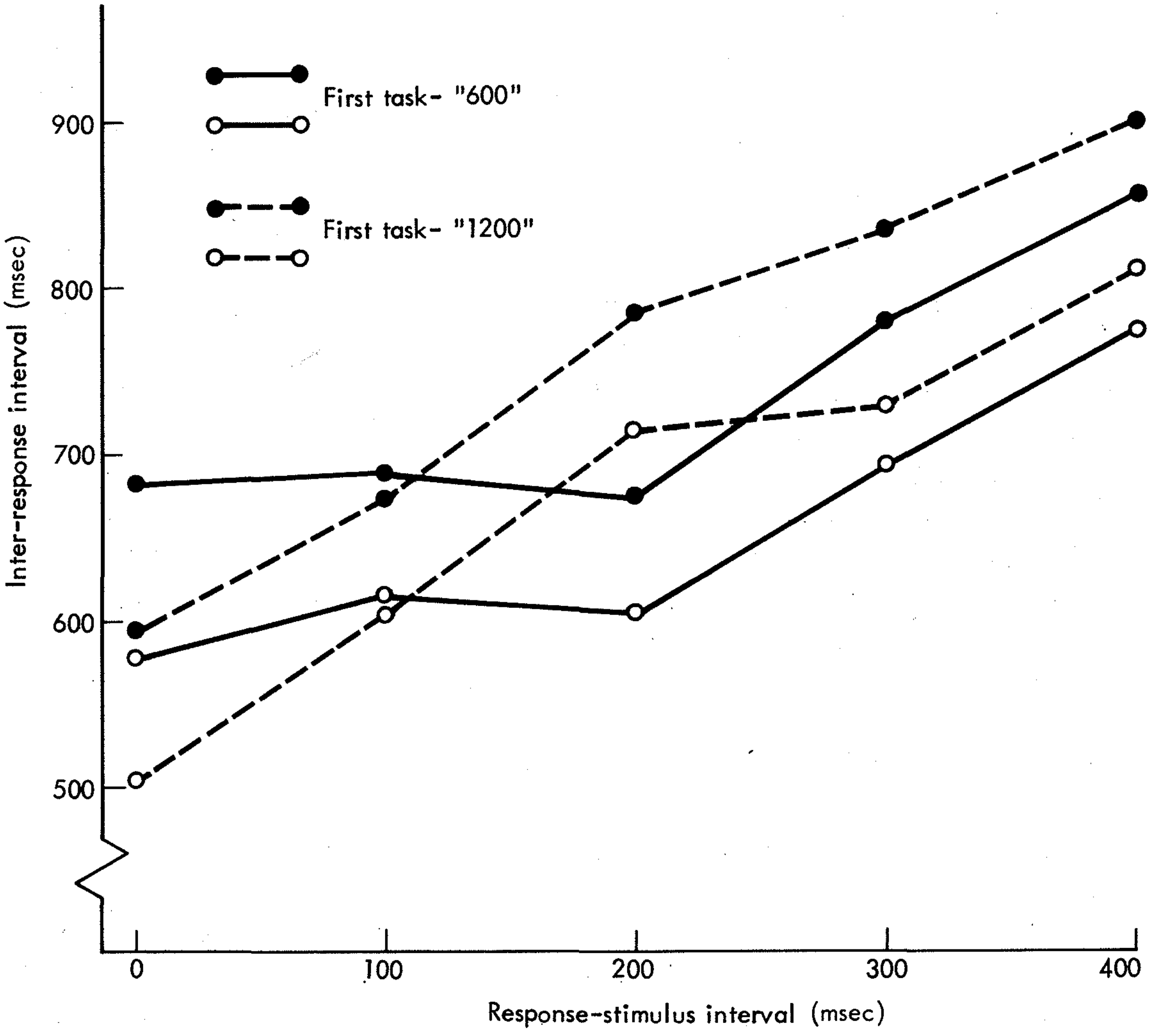

FIGURE 9-8
Data from Kafry (1971), with permission. Filled circles: data of 20 students. Unfilled circles: data of 20 flight cadets.

response, as if a stimulus that was shown at RSI = 0 did not become effective until 200 milliseconds later. In contrast, there was no indication of absolute refractoriness in the "1200" condition, where the effectiveness of processing, measured by the slope of the line, was about 75 percent of normal for several hundred milliseconds after the occurrence of R_1. The subjects' reports give a clue to the nature of the qualitative difference between the two conditions. In the "1200" condition, the subject has time enough to prepare for both tasks. Indeed, he may throw anticipatory glances at the light display while the counter runs. In the "600" condition, on the other hand, attention is riveted continuously on the counter, since the subject must "decide" to press the key when he sees the counter reach about 400, in order to execute the movement at the appropriate time. The inability to prepare for the next task is reflected in the prolonged refractoriness of this condition.

The two experiments that have been discussed in this section suggest that attention is focused exclusively on the first stimulus-response task only when that task is exceptionally difficult. When the first task is easier, some attention is diverted to the execution of the second task or to preparations for it, and the typical rising IRI function is observed.

OTHER FINDINGS AND THEORIES

The interpretation of the refractoriness paradigm as a special case of divided attention is similar in some respects to the *response-conflict* theory of the psychological refractory period which was originally presented by Reynolds (1964, 1966) and vigorously supported by Herman and Kantowitz (1970). This theory proposes that S_1 and S_2 elicit response tendencies that are likely to conflict. The responses to both stimuli will be retarded when such a conflict occurs, but it is assumed that the prepotent response suffers the smaller delay. A response is prepotent either by instruction or because it was already in preparation when conflicting tendencies were aroused. The latter factor, of course, always favors R_1 over R_2, and it explains why RT_2 is relatively slower than RT_1 in the double-stimulation paradigm. Response-conflict theory leads to the prediction that the interaction will be most detrimental if S_1 and S_2 are associated with incompatible or antagonistic responses. This prediction has been confirmed (Herman & Kantowitz, 1970).

The present interpretation of refractoriness and response-conflict theory shares the assumption that S_1 and S_2 can be processed in parallel. It is not obvious, however, how a response-conflict theory could account for the effects of task demands that were illustrated in the preceding section. In addition, response-conflict theory cannot readily explain the finding of major delays of R_2 in the RSI design (Kafry, 1971; Rabbitt, 1969), since there are no conflicting tendencies when S_2 is presented after the completion of R_1. The simplest explanation of these delays is that the preparation for a subsequent stimulus and a subsequent response demands effort. Under some conditions (see, e.g., Fig. 9-8), this preparation is precluded during the processing of another response.

Response-conflict theory and the limited capacity hypothesis both suggest that R_1 should be somewhat slower in the double-task situation than when it performed alone. Results confirm this expectation. Many studies have reported the consistent finding that the reaction to the first stimulus is slower in the double-task paradigm than when a single stimulus is presented (Bertelson, 1967; Broadbent & Gregory, 1967; Gottsdanker, 1969; Gottsdanker, Broadbent & Van Sant, 1963; Herman & Kantowitz, 1970; Nickerson, 1967; Smith, 1967c; Triggs, 1968). The delay is usually quite small (around 30 msec). The delay of R_1 has been found to vary inversely with ISI in some experiments: when S_2 followed S_1 in quick succession, RT_1 was slow (Herman & McCauley, 1969). The delay of R_1 also increases with the complexity of the processing that S_2 and R_2 require (Karlin & Kestenbaum, 1968). The competition between the processes leading to the two responses is further confirmed by the observation that the speed of R_1 and R_2 can be manipulated by instructions: as one of these responses is made faster, the other correspondingly slows (Triggs, 1968). Herman and Kantowitz (1970) have reviewed these effects in detail.

An important observation that must be considered in explaining refractoriness is that a stimulus which does not require a response can nevertheless delay the response to another stimulus. Thus, a large number of studies have shown that the interpolation of an irrelevant stimulus S_2 after S_1 causes R_1 to be delayed (Davis, 1959, 1962; Elithorn, 1961; Fraisse, 1957; Kay & Weiss, 1961; Nickerson, 1967; Rubinstein & Rutschman, 1967; Smith, 1967a). The delay is small (usually 40–60 msec), and its interpretation is controversial (Bertelson & Tisseyre, 1969; Davis, 1959; Herman, 1969). A larger delay has been observed where a stimulus S_1 *inhibited* a response. When S_2 was presented shortly after such an inhibitory stimulus, RT_2 was longer than normal (Sanders & Keuss, 1969). These results are consistent with a theory of limited and shared capacity, but they are also easy to explain within a response-conflict theory.

Bernstein (1970; Bernstein, Clark & Edelstein, 1969a, b) has reported the interesting finding that visual RT can be facilitated by presenting a loud auditory stimulus some time *after* the relevant visual stimulus. A plausible explanation of this effect is that the tone increases arousal and therefore facilitates ongoing processes. When the second stimulus is associated with competing response tendencies, RT is delayed (Herman, 1969).

A complete account of the interactions between stimuli and response in the double-stimulation paradigm must also include the effects of *expectancy* and *preparation.* In general, a subject's RT is shorter if the signal to respond arrives precisely at the instant it is expected. This is the expectancy effect. In addition, there is an effect of the foreperiod that is available for preparation: following a warning signal, it takes about half a second for a subject to be at his best. In the double-stimulation paradigm, the occurrence of S_1 provides a warning that S_2 will soon occur. The readiness to respond to S_2 will therefore increase gradually, reaching a maximum no sooner than 500 milliseconds after S_1. Furthermore, if the average value of ISI is longer, the gradient of maximal readiness for S_2 will shift toward the value of ISI at which S_2 is most likely to occur.

There has been a major attempt to describe the so-called refractoriness effect in terms of expectancy and preparation (Adams, 1962; Elithorn & Lawrence, 1955), but comprehensive reviews of the evidence have concluded that this attempt was unsuccessful (Bertelson, 1966; Nickerson, 1967; Smith, 1967b). In accordance with the predictions of expectancy theory, the average ISI affects RT_2 in the double-stimulation paradigm (Adams, 1962), suggesting that S_1 functions as a warning signal which causes the readiness for S_2 to increase, as in the foreperiod effect. However, the foreperiod effect in the single-stimulus case is smaller than the refractoriness effect, and therefore insufficient to account for it (Shaffer, 1968). Furthermore, refractoriness occurs in the absence of temporal expectancy effects, e.g., when the interval between the two signals is constant (Borger, 1963; Creamer, 1963). Thus, expectancy can be ruled out as a general explanation of refractoriness effects. Nevertheless, the idea that preparedness for a stimulus and for a response vary in time cannot be neglected, particularly in the explanation of refractoriness in the RSI paradigm, i.e., where the occurrence of S_2 follows the execution of R_1 (Kafry, 1971).

REVIEW

This chapter was concerned with the organization of performance in tasks that require two speeded responses. The suggestion was advanced that an analysis of the interval between the two responses (IRI) is often more illuminating than separate analyses of their latencies. The occurrence of response-grouping is indicated by an approximate constancy of IRI over conditions, and by a relatively low value of IRI. Evidence for response-grouping was found in a reanalysis of a study by Schvaneveldt (1969). More generally, it was proposed that the separability of the processes that lead to physically distinct responses must be demonstrated empirically, not assumed.

The application of an IRI-analysis to data in the refractoriness paradigm suggested that some results which have been interpreted as supporting single-channel theory actually provide conclusive evidence against that theory. Typical results in the double-reaction paradigm indicate that processing of S_2-R_2 typically begins as soon as S_2 is presented, and continues at an accelerated rate throughout the latency of R_1. An unexpected result observed in two studies (Karlin & Kestenbaum, 1968; Smith, 1969) is that the minimal IRI between ungrouped responses does not seem to depend on the complexity of the interacting responses, at least within the range of complexity included in these studies. The minimal IRI may correspond to a state of motor refractoriness.

Keele (1973) has argued from these observations that mental operations of perception, memory retrieval, and response selection require no attention and can be performed in parallel. His theory cannot account for the isolated conditions in which the predictions of single-channel theory are quite strictly upheld (Broadbent & Gregory, 1967, exp. 2; Kafry, 1971). A strategy of strictly serial processing was adopted in these experiments when the first response task was exceptionally difficult. No structural theory which assumes that processing is always serial, or always parallel, can account for these results, which tend to support the concept of a flexible policy of attention allocation.

Additional complexities of the refractoriness paradigm were briefly discussed in the last section. The concepts of preparation, expectancy, and response-conflict must be included in a comprehensive account of results in this paradigm. The refractoriness paradigm appears to be too complex to provide definite tests of theoretical positions concerning the division and the focusing of attention.

10

Attention and Task Interference

We often find it exceedingly difficult to execute two activities together, although each alone is easy. This mutual interference between concurrent tasks is sometimes explained in structural terms, on the assumption that the competing tasks simultaneously elicit incompatible responses, or impose simultaneous demands on specific perceptual or motor mechanisms. An effort theory seeks to explain interference in terms of a competition for a general limited capacity. This chapter reviews evidence which shows that concepts of capacity and of structure are both needed to explain the phenomena of interference. The results of some studies of dual-task performance are interpreted in terms of the effort theory introduced in Chapter 2, and the reader may find it useful to quickly scan the illustrations of that chapter before reading the present one.

CAPACITY INTERFERENCE

A theory which identifies attention with effort and with a limited capacity entails two predictions concerning interference between concurrent activities: (1) interference will arise even when the two activities do not share any mechanisms of either perception or response; (2) the extent of interference will depend in part on the load which each of the activities imposes, i.e., on the demands of the competing activities for effort or attention.

The support for both propositions is overwhelming. The activities of walking and mental arithmetic, for example, are as distinct as can be. Nevertheless, the following experiment usually succeeds: while walking casually with a friend, ask him to perform a complex operation of mental arithmetic; he is very likely to stop in his tracks. Even the highly automated act of walking apparently demands some central capacity.* Another example that was introduced earlier is the combination of driving and conversing. The conversation is interrupted when the demands of the driving activity become critical.

There is much experimental documentation for task interference that arises from capacity overload. Thus, Posner and Rossman (1965) asked their subjects to retain three letters for a brief interval, during which they engaged in mental tasks of varied complexity. The amount of retention decreased regularly with increasing difficulty of the interpolated task. Similar results have been obtained by many other investigators, with different combinations of memory task and interpolated activity (Baddeley, Scott, Drynan & Smith, 1969; Broadbent & Heron, 1962; Dillon & Reid, 1969; Murdock, 1965; Peterson, 1969). This finding is most naturally interpreted by assuming that rehearsal demands a considerable amount of effort or attention. When attention is preempted by the interpolated task, rehearsal is disrupted and retention suffers. This interpretation is not affected by the finding (Reitman, 1971) that a nonverbal interpolated task of signal detection may effectively prevent rehearsal without destroying the memory of the stored material. This finding implies that rehearsal is not always necessary to retard forgetting. When required rehearsal is precluded by concurrent activities, retention suffers.

Johnston, Greenberg, Fisher, and Martin (1970) employed tracking as a subsidiary task in several studies of memory. The subjects in one of these studies were shown lists that they were to recall after a retention interval. Tracking scores during the retention interval were inversely related to memory load, which presumably controls rehearsal activity. Tracking performance was also related to the complexity of an opera-

---

* It seems fair to raise the question of why I have been pacing the corridor while formulating the preceding sentences. The hypothesis I find most attractive is that walking is often used to pace oneself down, thus slowing the rate of thought and internal speech so as to minimize confusion. Deliberately slowing down is not advantageous in activities that impose a high load on short-term memory, such as mental arithmetic. Accordingly, one tends to stay still while performing such activities.

tion that the subject was asked to perform on material stored in memory (e.g., mentally arrange five words in alphabetical order). Finally, the activity of verbal recall of stored material caused severe interference with tracking. This result is consistent with physiological measures of effort, as well as with other studies of divided attention (Kahneman & Peavler, 1969; Kahneman & Wright, 1971; Trumbo & Noble, 1970).

In a related study, Shulman and Greenberg (1971) observed that the probability that a subject would recognize an item in a tachistoscopic exposure was inversely related to the length of a list that he was silently rehearsing at the time. However, the relation between perceptual deficit and memory load appeared to break down when the amount of material exceeded memory span. This interesting result confirms the suggestion that effort no longer increases when a task becomes impossibly difficult. The same authors also found that reaction time in deciding which of two lines is longer is delayed by concurrent rehearsal (Shulman & Greenberg, 1971; Shulman, Greenberg & Martin, 1971).

The interaction of learning activity with other tasks may follow different rules in motor learning, which does not involve rehearsal. Eysenck and Thompson (1966) reached the surprising conclusion that concurrent activity disrupts the performance, but not the learning, of a motor skill. Subjects pressed a foot pedal in response to auditory signals while learning to track on the pursuit rotor. The rate of foot responses imposed by the auditory signals was varied. The tracking performance deteriorated as the rate of this interfering response was increased, but the difference between groups exposed to different levels of distraction vanished as soon as the distraction was removed. Following a rest period, all groups showed a large reminiscence effect and precisely identical tracking ability. Eysenck and Thompson (1966) concluded that attention is not involved in the acquisition of skill during massed practice. This provocative conclusion demands further study.

A study by Keele (1967) provides strong evidence for a hypothesis of limited capacity. Keele instructed his subjects to turn off a series of lights; he controlled the difficulty of that task by the compatibility of the stimulus-response arrangements. In addition, the subjects were asked to count backward, by one, three, or seven. Measurements of the speed of both responses indicated some gain from performing the tasks together, when both were easy. The total time required to perform a certain number of responses of both kinds was less when two easy tasks were combined than when they were performed successively. When the tasks were both difficult, on the other hand, the attempt to combine or interweave them resulted in a marked loss of efficiency. As predicted by a capacity model, the quality of performance on each task decreased regularly with the difficulty of the other.

Schouten, Kalsbeek, and Leopold (1962) used a paced series of discriminations to induce decrements in various highly skilled activities. They presented striking instances of the deterioration of handwriting under conditions of load. Evidently, even highly "automated" performances depend on the limited capacity.

The dual-task method sometimes permits a sensitive analysis of task demands. For example, Garvey and Taylor (1959) found that involvement in mental arithmetic caused more errors in one variant of a tracking task than in another, although both variants were performed equally well in the absence of interference. The method can also be used to reveal hidden effects of practice. Thus, the quality of performance of the main task may remain ostensibly constant when learning is at a plateau, but performance of another task reveals that attentional demands diminish (Bahrick & Shelly, 1958). Brown (1964; Brown, Simmons & Tickner, 1966) has noted that a given level of *effectiveness* can be attained at different levels of *efficiency*. Effectiveness is a measure of the quality of performance, while efficiency is the relation between the quality of performance and the effort invested in it (Eason, 1963). Given constant performance of the primary task (i.e., constant effectiveness), an improvement in the performance of the subsidiary task indicates enhanced efficiency. Brown (1966) presented trainee drivers with successive series of eight digits, where one digit was altered on each repetition. The subjects were required to identify the alteration. At some stages of driving practice, this measure of "reserve capacity" discriminated between the trainees who eventually passed the course and those who did not, although objective measures of driving performance did not separate the two groups.

The dual-task design permits the comparison of different tasks in common units. This is achieved in the subsidiary-task method (Brown, 1964, 1968), in which the subject is instructed to perform the primary task as well as he can and to devote only the remaining capacity to another task. The quality of performance of this subsidiary task provides a measure of the load imposed by the primary task. Because such measures contribute both to psychological theory and to human engineering applications, there have been several attempts to devise standard subsidiary tasks.

A promising approach was introduced by Michon (1964, 1966), who required subjects to tap a regular rhythm while they engaged in various primary tasks. The rationale for the test was that "if someone is performing a difficult perceptual motor task, the problem is not *how* to do something else, but *when* to do it without disrupting the major cycle of action [Michon, 1966, p. 403]." Michon reported a fair degree of correspondence between the rated subjective difficulty of a set of primary tasks and the variability which they induced in tapping performance. Baddeley (1966) measured load by requiring subjects to produce a random series of digits. He observed that redundancy tends to increase under high load.

The results of these studies are generally encouraging. Nevertheless, Brown (1966, 1968) has listed several limitations in the use of subsidiary tasks to measure load. In particular, he noted that comparisons of different tasks require great caution, since the amount of disruption of the subsidiary task depends on the structure of the primary task, as well as on its difficulty. The subsidiary-task method does not provide a pure measure of capacity interference, because any particular combination of primary and subsidiary tasks is likely to involve some structural interference. Brown noted, for example, that Michon's interval-production task (Michon, 1966) is most severely disrupted by primary tasks in which the subject responds at a high rate, whereas Baddeley's (1966) random generation task appears to be sensitive to information load, rather than to response rate. Tasks that impose a high motor load and tasks that impose a high perceptual or conceptual load are therefore likely to have different effects on the subsidiary tasks that Michon and Baddeley introduced (Brown, Simmons & Tickner, 1967). The conclusion, of course, is that capacity interference is best measured by means of a battery of subsidiary tasks, rather than by a single task.

DECISION BOTTLENECK OR COMPETITION FOR EFFORT

The evidence of the preceding section is consistent with the notion of a general limit on capacity, but it can also be interpreted in other terms. Welford (1968) has proposed a single-channel theory, according to which interference arises in the dual-task paradigm when the two tasks compete for the control of the response-selection stage. In Welford's theory, this stage is a bottleneck, which can only deal with one response process at a time. This theory is formally similar to Broadbent's filter theory, except for the location of the bottleneck, which Broadbent placed at the P-system, and Welford placed at a stage which translates percepts into acts. In both theories, the effect of complexity on interference is explained in terms of time: the single channel is occupied for a longer period by a complex operation than by a simple one, and the severity of the interference increases with the duration of the delay.

The assumptions of single-channel theory are much more precise and restrictive than those of a limited capacity model which permits parallel processing. In particular, single-channel theory yields precise predictions for the refractoriness paradigm that was discussed in the preceding chapter. These predictions, however, have generally failed to be confirmed.

In the dual-task paradigm, single-channel theory entails that a task which does not require response selection should neither interfere with any other task, nor be subject to interference. In contrast, the limited capacity hypothesis entails that any two tasks should be mutually interfering to some extent, and that the extent of interference should vary with effort, rather than with requirements of response selection.

Results that support single-channel theory were reported by Trumbo, Noble, and Swink (1967), who combined a tracking task with several other activities. They found that tracking performance was disrupted equally by tasks of different difficulty. The following two activities, for example, interfered equally with tracking: a complex learning task, in which the subject serially anticipated each member in a series of stochastically dependent numbers; and an apparently much simpler task, in which the subject emitted a series of freely selected numbers. The general conclusion of the study was that the "a priori difficulty of the secondary task was not predictive of the amount of interference, nor was the extent of interference a function of primary task difficulty [Trumbo, Noble & Swink, 1967, p. 239]." The authors concluded that the initiation of responses was the main source of interference between concurrent tasks.

The results of this experiment cannot be accepted without reservation, because similar studies in which tracking was the primary task have reported a substantial effect of secondary task difficulty, even when the response elements of that task are kept constant (Johnston, Greenberg, Fisher & Martin, 1971; Naylor, Briggs & Reed, 1968). However, an additional study by Trumbo and Noble (1970) provides more compelling evidence for the conclusion of their original study. Trumbo and Noble adopted a theoretical framework suggested by Smith (1968), in which the stimulus-response chain is divided into four stages: (1) stimulus preprocessing; (2) stimulus classification; (3) response selection; and (4) response execution. They compared the effects of a series of secondary tasks, which were designed to impose different demands on each of these stages. The primary task was always the learning of a list of nonsense syllables, presented at a three-second rate. The following secondary task conditions were studied:

(*a*) Control. No task.

(*b*) Free response. Pressing one of five buttons, freely chosen, once every three seconds. This task involves only stages 3 and 4, i.e., the selection and execution of a response.

(*c*) Learning the stochastic rules governing a sequence of lights, shown at the rate of one every three seconds. This task involves only stages 1 and 2.

(*d*) "Shadowing" the series of lights, without learning instructions. Shadowing was done by pressing the button spatially corresponding to each light that came on. This task was assumed to involve stages 1, 2, and 4.

(*e*) Anticipating each of the lights by pressing the appropriate button. This task was assumed to involve all stages.

Condition (*e*) severely retarded verbal learning, and condition (*b*) was also disruptive. Conditions (*c*) and (*d*) did not differ significantly from the control condition. It is easily seen that this result implicates stage 3, response selection, as the locus of interference. This conclusion appears to support single-channel theory, since task (*c*) causes less interference than task (*b*) although it is more complex.

On closer examination, the results are consistent with the approach to effort which was introduced in earlier chapters. Indeed, one may predict with some confidence that physiological measures of effort, such as the dilation of the pupil, would reproduce the ordering of conditions obtained by Trumbo and Noble. Free choice of a response, as in condition (*b*), is known to elicit substantial pupillary changes (Simpson & Hale, 1969), whereas the dilations that accompany silent associative learning are small (Kahneman & Peavler, 1969). Thus, the finding that a "simple" task of free response causes greater interference than a complex learning activity is quite consistent with physiological studies of effort. Physiological studies also indicate that considerable effort is involved in overt tests of recall, which are present in condition (*e*) of the Trumbo-Noble experiment. Thus, the ordering of conditions by effort and by interference is probably the same, and this ordering violates intuitive notions of difficulty and complexity. However, a discrepancy remains, since Trumbo and Noble reported a dichotomy between some tasks which cause interference and others, including associative learning, which do not. Pupillary studies, on the other hand, suggest that the activity involved in associative learning does require effort. The pupillary dilations that accompany such learning are extremely consistent, although they are only 15–20 percent as large as the dilations that occur during tests of recall. The absence of statistically significant interference in some conditions of the Trumbo-Noble study could well be due to the difficulty of obtaining reliable and sensitive interference measures in a relatively small number of trials (Kahneman, 1970).

The reinterpretation of the experiment of Trumbo and Noble relies on speculations about what pupillary measurements would have shown, if collected. This type of reasoning is hardly conclusive. However, there exist experimental results that directly confirm the continuous covariation of a measure of interference with physiological indications of effort and arousal (Kahneman, 1970; Kahneman, Beatty & Pollack, 1967). These results were discussed in an earlier chapter (see Fig. 2-3 on page 21). The subjects in a series of experiments performed a demanding digit transformation as their primary task, and as a subsidiary task they monitored a visual display for a significant signal. Two of the curves in Figure 2-3 illustrate the time-course of the perceptual deficit that occurred during the transformation task, while a third curve traces concurrent changes of pupil size. Control experiments in which an artificial pupil was used showed that the dilations of the pupil were not the cause of the visual deficit. The observation of a close correspondence between behavioral and physiological measures provides strong support for an effort theory. Another important observation in Figure 2-3 is that the perceptual deficit was severe during the pause between the presentation of the digits and the subject's response. Thus, the interference with perception was due neither to the presence of concurrent stimuli nor to the occurrence of concurrent responses.

The present argument suggests a reformulation of single-channel theory. This theory assumed that the stage of response selection is a bottleneck, which can only deal with one response at a time. Instead, it appears plausible to assume that the selection of a response is often highly demanding of attention and effort. As a result, activities that demand response selection will tend to interfere with other activities. Response selection, however, is neither a necessary condition for the occurrence of interference, nor a sufficient condition for the total refractoriness postulated by single-channel theory.

PROBE MEASURES OF SPARE CAPACITY

The observation of a perceptual deficit that accompanies the transformation of a series of digits illustrates the use of a probe signal to measure variations of spare capacity during the performance of a primary task. To obtain such a measure, the probe must be introduced at an unpredictable time. According to the theory of effort outlined in Chapter 2, the accuracy and the speed of the response to an unpredictable probe reflect the spare capacity that is allocated to perceptual monitoring at the instant of presentation. The theory assumes that spare capacity decreases regularly with increasing investment of effort in the primary task (see Fig. 2-1 on p. 15).

Two measures of the response to the probe have been used in recent studies: perceptual deficit and delayed RT. Anat Ninio, at the Hebrew University, has investigated variations of perceptual deficit as a function of task load during the performance of a reaction task. She showed the subject a very large numeral, projected on a screen. The subject was required to read the numeral aloud (Add-0) or to transform it (Add-1). His primary task was to perform this operation as fast as he could, and he was rewarded for consistent maintenance of a fast RT. Some time after the presentation of the numeral, an acuity target was briefly shown, preceded and followed by a masking field to prevent visual persistence. Acuity was found to vary sharply during the reaction time to the numeral in both task conditions. At about 150–300 milliseconds after the presentation of the numeral, acuity was significantly lower when the subject was engaged in the Add-1 task than when he was engaged in the Add-0 task. Earlier and later, there were no significant differences.

Ninio's study was undertaken in the hope of clearing up a thorny problem in the theory of effort: the confounding of effort with response time. In general, there is a high correlation between the time required to produce a response and the physiological arousal that accompanies that response. Because all autonomic measures of effort involve some lag and temporal integration, these measures cannot be used to prove that the *rate* at which effort is exerted is higher with a slow and difficult response than with a faster and easier one. The results of Ninio's experiment suggest that a more complex response task involves both a longer latency and a greater investment of effort during at least some segments of this latency.

A study by Blake and Fox (1969) yielded discrepant results. These authors presented an acuity target at various intervals during the reaction time to an auditory tone, and observed no decrement of visual recognition. This unexpected failure to obtain interference could be due to a combination of two factors: a very simple and fast manual task (RT was 150–200 msec) and a mode of target presentation which permitted prolonged visual persistence. It is at least possible that the subjects in this study "read" the acuity target from an iconic image. The persistence of this image would permit the subject to deal with the two tasks in sequence. This strategy is precluded when the probe stimulus is immediately masked.

Posner and Keele (1968, 1970) have used simple RT as a subsidiary task. At various times during the execution of a visually guided movement, they introduced an auditory signal to which the subject was to respond. The RT to the probe was longer if the probe coincided with the initiation of the movement or with its terminal phase than if it occurred during the intermediate period. In a further refinement, Ells (1969) showed that the RT to a probe inserted just before the initiation of a choice-response reflects the complexity of the choice (i.e., the number of alternative responses). On the other hand, the RT to probes inserted during the movement reflects the accuracy demands of the task (i.e., the size of a target toward which the movement is aimed).

Probe RT was used in a subsequent study (Posner & Boies, 1971) to investigate a letter-matching task. The sequence of events on each trial was as follows: there was a warning signal; some time later, a letter was shown; then another letter was shown and the subject pressed one of two keys with his right hand, depending on whether or not the second letter was the same as the first. A tone was presented on half the trials, in one of eight temporal positions. The subject was instructed to press a key with his left hand whenever he heard the tone, but the instructions and the knowledge of results that the subjects were given both emphasized the letter task. The RT to the auditory probe was interpreted as a measure of the demands of the letter-matching task.

Posner and Boies (1971) observed that the presentation of the first letter in the sequence did not cause an immediate rise in probe RT. During the first 300 milliseconds after the presentation of the initial letter the subject is presumably involved in an operation of encoding, which prepares him to judge whether the second letter is the same as the first. Probe RT was not significantly delayed by this encoding activity. However, RT started to rise about 500 milliseconds before the presentation of the second letter. When the interval between the first and the second letter was prolonged, the rise in probe RT was correspondingly delayed (Posner & Klein, 1972).

Posner interpreted probe RT as a measure of competition for a limited capacity, but it is not entirely clear that the delay of RT which is observed in the letter-matching studies provides a pure measure of capacity interference, since there seems to be little for the subject to do during the 500 milliseconds that precede the presentation of the second letter. A conflict between the anticipation of a response with the right hand and the execution of a response with the left hand could contribute to the delay. This interpretation is supported by a comparison of the magnitude of the delays observed by Posner and Boies to those obtained by Shulman and Greenberg (1971; Shulman, Greenberg & Martin, 1971), cited earlier. Although involvement in rehearsal delayed RT very consistently in these studies, the effect was much smaller than in Posner's paradigm, where the subjects are instructed to make two speeded responses. The similarity of the primary and subsidiary tasks probably increases conflict and interference.

A subsequent study (Posner & Klein, 1972) provided additional evidence for the validity of probe RT as a measure of task load. Enormous delays were observed when the subject was instructed to apply a transformation to the first letter and to match the second letter to the output of the transformation. The subject was to make a positive response if the second letter occurred in the alphabet three positions after the first (e.g., the response was positive if the first letter was M and the second was P). This task certainly keeps the subjects very busy during the brief interval between the first and the second letter. Accordingly, they tend to delay responding to the probe until the completion of the matching task.

This brief discussion of the perceptual-deficit and probe-RT methods echoes the conclusions reached earlier in the discussion of measures of continuous load. The object of all these methods is to measure the attentional demands of primary tasks, but the results of any single method must be interpreted with caution, because of the ever-present possibility that the observed interference is due to structural factors rather than to limitations of capacity. The methodological moral is clear: effort or load should always be measured by at least two independent methods, so chosen that they are unlikely to cause structural interference in the same way. For example, a perceptual subsidiary task minimizes overt responses, but it usually involves some load on short-term memory; a probe-RT task causes response conflict, but imposes no load on memory. The two methods appear to be complementary. Alternatively, either of these methods could be used in conjunction with physiological measures of effort and arousal (see Chap. 2). The time-lags involved in autonomic responses, however, make them inadequate for the study of the microstructure of effort demands. For that purpose, the only alternative to convergent behavioral measures may be a combination of a behavioral method with measurements of evoked cortical responses (e.g., Posner, Klein, Summers & Buggie, 1973; Posner & Warren, 1972).

PERCEPTION AND EFFORT

An important outcome of Posner's work (Posner & Boies, 1971; Posner & Klein, 1972) was the conclusion that the process of encoding does not require the limited-capacity mechanism: probe RT remained unchanged or even decreased during the first 200 milliseconds after the presentation of the initial stimulus in the matching task. Since the first signal must be encoded at about that time, the absence of interference with probe RT suggested that the process of encoding is effortless.

Keele (1972) has used a reaction-time measure in another attempt to demonstrate that certain mental activities are effortless. His subjects were required to make a choice-response to the color of a visual stimulus, which was sometimes a nonsense shape, sometimes an irrelevant word, and sometimes a color word (e.g., the word Green printed in red, with "red" the correct response). There was no difference in RT between the responses to nonsense shapes and to irrelevant words. Nevertheless, Keele could prove that words were read, because the presentation of color words caused significant interference. He concluded from this finding that reading a word is effortless and demands no attention. As was mentioned in the preceding chapter, Keele (1973) takes the position that all mental operations prior to the initiation of responses require no attention, and therefore do not interfere with other activities.

The view of perception introduced in Chapter 5 suggests a different interpretation of these results. It assumes that effort is invested in perception. The allocation of effort or attention to a particular perceptual object is manifested in figural emphasis. The effect of this allocation is to enhance the quality of the information which eventually reaches the recognition units. The number of activated recognition units and their degree of activation are affected by the amount of attention that was paid to the stimulus object. However, the activation of recognition units and the achievement of perceptual interpretations do not require more attention than was already allocated at the stage of figural emphasis. Thus, it takes no more effort to look attentively at a familiar English word than at a nonsense form. Whether such an attentive look results in "reading" the word depends entirely on the availability of a recognition unit for the pattern.

The occurrence of perceptual deficit during mental activity provides the most direct evidence for the relation between perception and effort. If an activity can be carried out without effort, it should no more be subject to capacity interference than be the source of such interference. Indeed, the most sensitive test of whether an activity demands effort is whether it can be disrupted by intense involvement in another activity. An act that demands little effort may be vulnerable to interference, while having negligible effects on other acts.

This methodological criticism of the Posner-Keele argument suggests that perceptual emphasis could demand attention after all. But a more significant aspect of this debate is conceptual: what is meant by saying that an activity requires or demands effort? These verbs have two distinct meanings: one, that we may label demand_1, merely states a necessary condition for some end to be achieved. The other meaning, demand_2, implies that some action is taken to ensure that the demand will be met. Thus, it is proper to say that a particular flower demands_1 a great deal of water for normal growth, while a child loudly demands_2 more marbles from his partner.

It will now be apparent that the terms "demand" and "require" have been used in the preceding discussion in the two meanings of $demand_1$ and $demand_2$. Thus, it was said that many mental activities $demand_1$ effort, because they cannot be completed without attention. In addition, some stimuli which are favored by a selective set $demand_2$ attention, i.e., they attract more attention than do other stimuli. Finally, the model of attention introduced in Chapter 2 assumed a feedback loop by which an evaluation of current performance controls arousal, and thereby the supply of effort for the successful continuation of that performance. It is through this feedback loop that a continuous mental activity $demands_2$ attention and effort. Thus, a complex task such as serial digit transformation cannot be carried out without attention ($demand_1$) and it also causes attention to be mobilized ($demand_2$). The elicitation of the orienting response was explained in similar terms: the processing of a novel and significant stimulus requires ($demands_1$) a relatively large amount of effort; a significant violation of the neuronal model causes ($demands_2$) a subsequent surge of arousal and effort, which is directed to a more detailed analysis of the stimulus.

Most stimuli, of course, do not elicit an orienting response, and it is a reasonable assumption that most perceptual activity rarely $demands_2$ any effort, although it depends on the continuous allocation of some capacity ($demand_1$). If this idea is correct, minor changes in the structure and complexity of perceptual acts will have no effect on the performance of concurrent activities. The absence of interference between simultaneous dichotic items in our recognition studies was explained in similar terms (see p. 149).

Another result that requires an explicit distinction between $demand_1$ and $demand_2$ was obtained in studies of monitoring for targets identified by voice or by content, which were described in Chapter 8. Monitoring for a target defined by the sex of the speaker is certainly not more difficult than monitoring for a semantically defined category: it $demands_1$ no more effort. Nevertheless, the recognition of a word presented concurrently with a target was more severely disrupted when that target was identified by voice than by content. This finding was explained on the assumption that a physically distinct target $demands_2$ attention very early in perceptual analysis, while a content target must activate the recognition system before it $demands_2$ attention (see p. 152). The concurrent word presented to the other ear can be processed normally until attention is withdrawn to deal with the target. In this manner, a relatively easy monitoring task causes greater interference than a more difficult task, precisely because it involves a rapid redirection of attention.

The distinction between $demand_1$ and $demand_2$ provides the rationale for the use of visually masked stimuli as probes in the measurement of spare capacity. Studies of the duration and locus of fixations indicate that attention can be quickly directed to a potentially significant stimulus that is not immediately identified. The fixation on a significant stimulus can also be extended—a decision that is certainly made within 150–200 milliseconds of the initial fixation. If the potential target was first viewed in the visual periphery, a tentative detection can control the choice of the next fixation (Gould & Schaffer, 1965). In these examples, an activity of perceptual analysis demands$_2$ attention. However, a delayed allocation of attention cannot affect perception if the stimulus is immediately removed and its trace destroyed by a subsequent mask. In this manner, the use of masked stimuli provides a pure measure of the attention that was allocated to visual perception at the instant of presentation.

Set and Other Determinants of Effort Demands

While the preceding section concluded that perceptual activity demands effort, it also implied that these demands are slight, when compared to those of other activities. Choices, decisions, rehearsal, and the mental manipulation of stored symbols, all appear more demanding than routine perceptual analysis. These activities are particularly demanding when executed under pressure of time. Thus, the rate at which mental activity is performed is a primary determinant of effort. In many activities, "taking it easy" simply means to slow down. There are activities, however, which impose their own rate. This is especially true of any mental act that depends heavily on short-term memory, since the rate of rehearsal must compensate for the rate of decay of stored information. In such tasks, one simply cannot "take it easy."

A concept of rate becomes meaningful only when the units of activity are specified. However, the unit of activity is an elusive concept, because of the hierarchical character of action. What is the unit, for example, when one recites the alphabet? Is it the individual phoneme, the individual letter, or perhaps such familiar groups as ABCD . . EFG . . HIJK . . LMNOP? If the analogy of perceptual grouping is accepted, the answer to such a question is not arbitrary. A certain level of organization may be dominant. Intuitively, it seems that performance is monitored at the completion of units at that level, and that decisions and choices are formulated in terms of these units.

In his classic paper on the serial organization of behavior, Lashley (1951) introduced a vivid example. Imagine a piano with a defective key that cannot be depressed. Any piano player will stop playing when he unexpectedly encounters such a key. However, the expert player will normally play several additional notes before he stops. Evidently, the checkpoints at which behavior is monitored and controlled do not occur after each note. Miller, Galanter, and Pribram (1960) expressed the same idea in their notion of the TOTE. They analyzed behavior as a sequence of operations, with an objective defined for each such operation. When the operation is completed, a test is carried out to confirm the attainment of the objective. Only then is the control of action passed on to the next objective. Thus, a continuous activity can be analyzed in terms of units of Test-Operate-Test-Exit. The rate of activity is best viewed as the number of TOTE's required per unit time. This may be the reason why Peterson (1969) found that such activities as rapid counting or speeded recitation of the alphabet did not cause a total disruption of concurrent mental activities. With such highly overlearned sequences, a large number of distinct muscular activities are packed into each TOTE.

The achievement of the most effective and economical organization of action depends in large measure on the degree to which the task allows anticipation of future stimuli and responses (Adams, 1966; Poulton, 1952; Shaffer & Hardwick, 1969a, 1970; Shaffer, 1971). Activities such as driving an automobile, reading, or shadowing an auditory message usually permit the performer to anticipate each response before he actually executes it. In reading aloud, for example, the anticipation is provided by the eye-voice span: the subject's eye is usually several words ahead of the word that he utters at any one time. The eye-voice span is easily measured by turning off the light by which the subject reads; he will almost invariably continue to "read" a few words after the light is off. In shadowing an auditory message, subjects typically adopt an average lag of 1–1.5 seconds, which allows them continuous advance information about the phrase that they will utter in the immediate future. The possibility of anticipation is essential to adequate performance. In typing, for example, "response may lag the fixated letter by six or seven letters, on the average, and . . . if lag is prevented by eliminating preview of text, then typing is about five times slower [Shaffer & Hardwick, 1970, p. 425]." Anticipation facilitates performance in several ways: it permits response integration, and thereby effectively reduces the number of discrete choices and decisions that must be made. It also permits a smooth adjustment of effort to the difficulty of each choice and each response.

Anticipation is but one of the adjustments of which man is capable, which reduce the effort required for adequate performance, or ensure that the supply of effort will meet the demands. These adjustments are often grouped under the collective label of *set*. The present treatment has distinguished several classes of preparatory adjustments.

A state of *perceptual readiness* for a particular perceptual interpretation increases the likelihood that this interpretation will be adopted, both when sensory information is appropriate to it, and when the match between the features of this information and the critical features of the relevant recognition unit is less than perfect. Perceptual readiness is mediated by a criterion bias favoring some interpretations over others. A state of readiness for a particular interpretation implies that the achievement of this interpretation demands_1 less information input, and less attention, than does the achievement of other interpretations. Thus, a stimulus for which one is ready is likely to be identified even when it is presented on an unattended channel, or at a low level of intensity or clarity.

A state of *response readiness* similarly lowers the criterion for the elicitation of a particular response, or class of responses. It is reasonable to assume that a response for which one is ready demands_1 less effort than does a response for which one is not prepared.

Perceptual and response readiness may be viewed as altered states of the specific units which are activated in the processes of perceptual interpretation and response selection. In contrast, *selective set* is a characteristic of the allocation policy that controls figural emphasis and other manifestations of selective attention. Here, a selected stimulus demands_2 attention: more attention or effort is allocated to it than to the processing of other stimuli. Two variants of selective set have been distinguished, of which one is mediated by the immediate allocation of attention to stimuli isolated at an early stage of analysis, while the other involves recognition units and a recursive path of attention control.

The primary mechanism of selective attention may be identified with Broadbent's filter. Perceptual emphasis is allocated to stimuli that possess a particular attribute, e.g., sounds that originate in a particular place or words printed in a particular color. A search set could affect processing by the same mechanism, and it is conceivable that a target for which one is set can attract attention prior to the activation of the recognition system, if the target is identified by obvious physical characteristics. A selected stimulus attracts more attention than do other stimuli. Thus, a stimulus for which one is prepared will "jump" from the background (e.g., Eriksen & Collins, 1969a; Neisser, 1967). An attended stimulus will also have prior entry, i.e., it will appear to have occurred sooner than a physically simultaneous unattended stimulus (Sternberg, Knoll & Gates, 1971). The reaction to a stimulus that matches expectation is speeded (Egeth & Blecker, 1971). Indeed, some components of the evoked cortical response occur sooner when the stimulus matches expectations than when it does not (Posner, Klein, Summers & Buggie, 1973). The effects of selective attention on the sensitivity parameter of signal detection can be mediated by this type of selective set.

Secondary selective attention is controlled either by a tentative recognition of a significant stimulus, or by a failure to obtain an adequate perceptual interpretation for an event which violates the neuronal model of expectations. Such stimuli demand$_2$ attention, which is allocated to them via the recursive path of attention control. This mechanism is involved in some search tasks (e.g., monitoring a list for names of animals). The tentative detection of the selected stimulus probably causes a surge of effort, as well as a redirection of attention to the detected target.

The various mechanisms of set are not mutually exclusive, and more than one mechanism may be engaged in any task. Thus, a set to search for animal names may increase the perceptual readiness for these names; it may also sensitize the process of secondary selective attention, so that a tentative recognition of a target item will cause especially detailed analysis of that item. Preparatory adjustments appear to be highly flexible.

Other aspects of preparatory set are the elicitation of anticipatory arousal, and of a specific posture of orientation. The warning signals commonly used in studies of reaction time and of the perception of brief stimuli serve both these functions of orientation and arousal. To be fully effective, such a warning signal must be delivered about 500 milliseconds before the relevant stimulus. Achieving a state of optimal readiness takes time. Studies of the foreperiod effect also indicate that optimal readiness cannot be maintained very long. Responses to stimuli that follow the warning signal by a second or more tend to be slower than when the foreperiod is half a second. This failure to maintain readiness is consistent with the hypothesis that arousal is largely controlled by the feedback of ongoing activity. In the absence of such feedback, arousal diminishes.

The alerting function of warning signals has been studied in detail by Posner (Posner & Boies, 1971; Posner, Klein, Summers & Buggie, 1973). He concluded that the presentation of the initial letter in the letter-matching task can facilitate performance both by increasing alertness and by increasing the specific readiness for the repetition of that letter. The two facilitative effects summate without interacting. This finding suggested the hypothesis that the encoding process which mediates the specific readiness for a letter is equally effective at various levels of arousal. An additional discovery concerned the nature of the foreperiod effect: Posner was able to show that the U-shaped function which relates RT to the duration of the foreperiod is associated with a

∩-shaped function for errors in a spatial choice-reaction. The high level of alertness at the "optimal" foreperiod is accompanied by a relatively high rate of errors.

There is other evidence which confirms the conclusion that high arousal tends to be associated with a lowered response criterion, and consequently with faster and less accurate responses (Broadbent, 1971). Posner's interpretation of these results is novel: he argues that alertness does not affect the quality of the information which is available to the decision mechanism, but merely the speed at which the decision is reached. Because the decision is reached faster when alertness is high, it is based on a reduced sample of evidence, and is consequently more subject to error than when alertness is low.

It is very unlikely that the adequacy of perceptual analysis was the limiting factor in these experiments. Indeed, different results are obtained when the stimuli for a task of simultaneous discrimination are brief and faint: with such stimuli, an anticipatory warning signal reduces both the latency of responses and the probability of errors (Posner, Klein, Summers & Buggie, 1973). Posner's interpretation is that a slow response (associated with low alertness) does not yield the advantage of a more protracted analysis when the stimuli are brief. An alternative interpretation is that anticipatory alertness facilitates the immediate perceptual analysis of stimuli, and also tends to alter the response criterion. When the stimuli are prolonged and easily perceptible, the only measurable effect of the warning signal will be an altered value on the speed-accuracy function. These are conditions where erroneous responses do not reflect perceptual errors. The advantage of anticipatory allocation of attention only becomes evident when errors of perception begin to limit performance. In this view, anticipatory arousal improves perceptual analysis, but does not facilitate the operation of the other mechanisms that determine the choice of a response in a discrimination task.

The preceding discussion of anticipatory adjustments indicates that these adjustments affect both the amount of attention required for the execution of an activity and the likelihood that attention will be effectively allocated to that activity in preference to others. These considerations introduce severe complexities in any analysis of performance in dual tasks, since the tasks interact at the level of preparatory set as well as during the performance of demanding activities. This interaction is sometimes favorable: the anticipatory mobilization of effort for a primary task occasionally facilitates the response to a probe signal (Posner & Boies, 1971). More often, the interaction is detrimental. There is much evidence that a "divided set" hampers performance. In the refractoriness paradigm, for example, the reaction to the first stimulus is generally slowed by the anticipation of another response (Smith, 1967c; Triggs, 1968). Similarly, Broadbent (1956) found that subjects often fail in a coding task when merely waiting for a buzzer to sound, and Malmo (1966) reported that subjects who expect to shift from one mode of tracking to another track less efficiently than under unified set. Webster and Solomon (1955) also observed that the comprehension of a single complex message is impaired if the subject had expected the presentation of two simultaneous messages. Two plausible interpretations of these findings are: (1) the divided set requires the maintenance of an orientation pattern which is both more strained and less effective than in unitary set; (2) the organization of divided set draws directly on the capacity of the organism.

STRUCTURAL INTERFERENCE

The introduction to this chapter distinguished two types of interference between tasks: capacity interference, which arises as a function of the attentional demands of competing activities; and structural interference, which occurs because the activities occupy the same mechanisms of perception or response. Structural interference in perception was illustrated in Chapter 8, where it was shown that concurrent monitoring tasks in one modality tend to be more difficult than concurrent monitoring in different modalities (Treisman & Davies, 1972). This study illustrates the general method by which structural interactions can be demonstrated. Tasks A and B are equated by difficulty or by a physiological measure of effort, when performed singly. If the combination of task A with a new task C is more demanding or difficult than the combination of tasks B and C, this result provides evidence for interference between A and C beyond what can be explained in terms of attention or capacity. The alternative interpretation, that tasks B and C are mutually facilitating, also assumes a structural interaction.

Structural interference appears to have been a confounding factor in several of the studies that attempted to measure capacity interference. Thus, Brown (1966) noted that the subsidiary tasks of interval production and random-number generation are affected differently by primary activities that involve a high rate of overt responses or a high rate of mental activity. Similarly, there are indications that probe-RT measures are especially sensitive to the motor component of the primary activity. The general rule appears to be that similar activities tend to be mutually interfering, unless they can be integrated.

Structural interference can also arise within a single task, through an interaction between the modality of the response and the modality of the input that controls the response. Brooks (1968) has offered an elegant demonstration of this effect. In one of his experiments, he briefly presented a line diagram (e.g., Fig. 10-1A), and later required subjects to begin at the star and categorize successive corners by saying "yes" if the corner is on the extreme top or bottom and "no" otherwise. The correct sequence of answers in this example is "yes,yes,yes,no,no,no,no,no,no,yes." Three modes of response were compared: calling out the words "yes" or "no" for each corner; pointing to the appropriate word in columns of "yes" and "no" (Fig. 10-1B); tapping with the left hand for "yes," and with the right hand for "no." The first response was purely vocal, while the second required visual monitoring. Subjects had much more difficulty with pointing than with the other modes of report. In another condition, the subjects heard a sentence (e.g., "A bird in the hand is not in the bush") and were asked to recall the sentence and to categorize each word as a noun ("yes") or any other part of speech ("no"). The same three modes of response were used, but now the vocal response was by far the most difficult. Brooks (1968, p. 354) remarked: "The subjects reported that they 'could say the sentence to themselves' while tapping or pointing, but not while saying 'yes' or 'no.' The diagrams could be 'pictured' while the subjects were tapping or saying 'yes' or 'no,' but not while they were trying to point."

Brooks (1967, 1970) also showed that reading and visualization are mutually interfering. Subjects were given a verbal description of a spatial arrangement, and were asked to imagine and describe a rotation of that

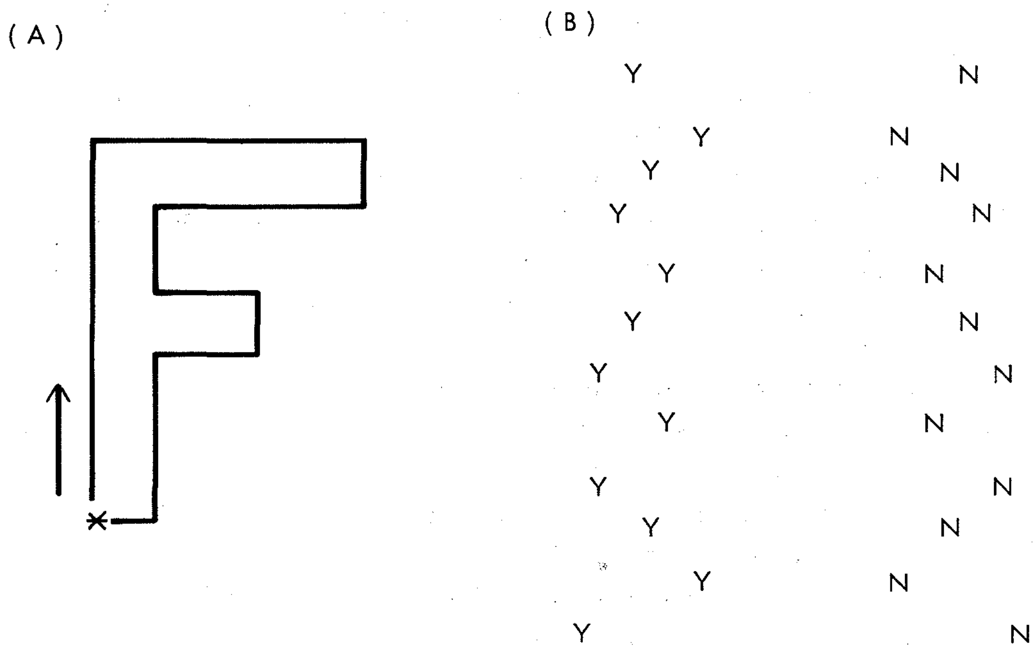

FIGURE 10-1
(A) Example of a stimulus in Brooks' (1968) study (with permission). (B) Display used in pointing task.

arrangement. They were able to do so faster if they merely listened to the original description than if they also read it. Structural interference occurs between visual operations within a single task.

Others have reported related findings. Lowe and Merikle (1970) found that spoken recall causes more output interference with the retention of auditory material than does written recall. Greenwald (1970a) found that people are better able to resist auditory distraction when they write than when they speak. Greenwald (1970c) reviewed James' ideomotor theory of action, which explains such interactions by the idea that images are involved in the control of action. A subject who prepares to utter a word produces anticipatory acoustic imagery, and this imagery may be disrupted if he hears a spoken word at the critical time.

These results extend the conclusion that simultaneous inputs on a single modality are likely to be mutually interfering. Interference is also likely when one modality is simultaneously involved in the control of response and in the discrimination of inputs. Thus, concurrent tasks that involve the same modality or response system are likely to suffer from structural interference.

The suggestion that all interference between tasks may be structural was advanced by Allport, Antonis, and Reynolds (1972). They proposed that an appropriate model of man may not be a single general purpose computer, but rather "a number of special purpose computers (processors and stores) operating in parallel and, at least in some cases, capable of accepting only one message or 'chunk' of information for processing at one time [p. 233]." As evidence, the authors showed that shadowing an auditory message impairs retention of a concurrent list more severely if the list is auditory than if it is visual, and more severely if the visual material consists of words than of pictures. In addition, they showed that experienced piano players could sight-read and shadow an auditory message at the same time with little evidence of interference. The authors justly emphasize the observation that subjects who shadow an auditory message can play the piano, but cannot effectively listen to another verbal message.

In contrast to these results is the finding of Peterson (1969) that complex covert problem-solving, including the solution of anagrams, can be carried out while the subject is engaged in continuous high-speed counting or recitation of the alphabet. Evidently, the involvement of verbal mechanisms in both tasks does not entirely preclude parallel performance. Interference was primarily determined by task complexity in Peterson's study. These results present a difficulty for Allport's multichannel theory.

Structural interference between related tasks suggests the image of antagonistic interactions among neural structures, such that a high degree of activation of one structure tends to reduce the level of activity in others. This mode of organization is prevalent in the nervous system, where it appears both in sensory analysis and in the control of motor output. An enhanced input is required to keep any unit in such a system at a specified level of response when another unit is simultaneously activated. Thus, the simultaneous operation of two antagonistic units demands$_1$ a greater input than the sum of the inputs that are required for separate operations. The strength of the inhibitory connections usually depends on the functional separation between the interacting units. Neighboring units tend to interact more strongly than distant units. It is readily seen that this feature of neural organization is quite compatible with the suggestion by Allport (1971; Allport *et al.*, 1972) and by Treisman (1969; Treisman & Davies, 1972) that similarity between interacting activities is the primary determinant of interference.

For an effort theory, the occurrence of interactions between tasks is a complication, because the attractive notion that effort demands of concurrent tasks are additive must be abandoned whenever such interactions occur. It is obviously impossible to predict the amount of interference between two tasks solely on the basis of their separate demands for effort. Overlap, similarity, and mutual compatibility must also be considered. However, it appears equally impossible to account for the phenomena of interference without reference to the role of task difficulty. Thus, it is useful to retain the term of structural interference for situations of strong interaction between similar tasks, and to apply the label of capacity interference to situations where difficulty is the main determinant of results.

INTERFERENCE AND EFFORT THEORY

Let us now recapitulate the major assumptions that appear to be required to explain the phenomena of task interference. First, we must assume the existence of performance units, roughly equivalent to the perceptual units that were discussed in Chapters 5 and 7. Attention, or effort, is allocated to such units. We assume further that each such unit is characterized by a certain level of demands, i.e., of need for attention or effort. Performance falters if the amount of attention allocated to a performance unit is less than the amount demanded. A further assumption is that the amount of attention or effort supplied to a unit rises with demand, but not sufficiently (see Fig. 2-1 on p. 15). When a task is made more complex, performance slows down and errors increase in spite of augmented effort.

Consider now the case in which two distinct performance units are simultaneously selected. We assume that these units are non-redundant, so that there is no possibility of integrating them into a superordinate structure. The perceptual equivalent would be the presentation of two different words to both ears at the same time, where both must be identified. When the units are non-redundant, it is reasonable to assume the following inequality:

Demand of Joint Performance $\geqq$ Sum of Separate Demands.

The difference between the left-hand and the right-hand sides of this inequality is a measure of structural interference. If the two performance units are incompatible or otherwise mutually antagonistic, the effort required to perform both together will be greater than the sum of the effort required to perform them separately. In addition, the total effort required to perform two acts together can be greater than the sum of separate demands, if the organization of joint performance itself demands attention (Lindsay, Taylor & Forbes, 1968; Moray, 1967; Taylor, Lindsay & Forbes, 1967).

The assumptions stated so far entail the prediction of some interference for all cases in which non-redundant tasks are performed together, even in the absence of structural interference. The basic assumption of the model is that the supply of effort is a negatively accelerated function of demand. Since the joint demands of two performance units are greater than the demands of either, the total deficit must be larger in joint performance than when the tasks are executed in isolation. Thus,

Total Deficit $\geqq$ Sum of Separate Deficits.

According to the assumption that supply is an increasingly insufficient response to demand, the total deficit increases with the total demand. Consequently, there will be little interference when both tasks are easy, and interference will increase with the difficulty of either task.

In this conception, interference is explained by the shape of the function that relates the supply of effort to the demand. This assumption is proposed instead of the commonly stated notion that a general limit on capacity explains task interference. The idea of a constant limit on capacity is inadequate, since it is easy to show interference occurring even in situations where the actor does not exert the maximal effort of which he is capable.

The preceding considerations indicate that interference must occur whenever two distinct tasks are performed together. However, the actor has considerable freedom to determine which task will suffer interference. Subjects are capable of protecting one task, so that it is performed in conjunction with another nearly as well as in isolation, and the entire interference effect is then found in the performance of the subsidiary task (Kahneman, 1970).

The treatment so far has assumed that the competing units of action are performed in parallel. This assumption was made because of the well-documented failure of various single-channel models. However, the maintenance of parallel organization of processing can sometimes lead to a total failure of one or both acts, and a sequential strategy must be adopted to prevent such overload. When the two tasks both consist of serial units of performance, the units of both tasks are often interleaved. Indeed, a basic rule of the policy that allocates attention appears to be that jamming of the system is not permitted to occur. When the demands of two tasks cannot be adequately satisfied, one is typically selected and the other is delayed or abandoned.

A similar conclusion was reached earlier in the discussion of dual monitoring. When two targets are presented at once, the typical outcome is for one to be perceived and for the other to be ignored entirely. If the subject is expecting the simultaneous occurrence of the two targets, processing is sometimes parallel and sometimes strictly sequential. The choice of processing mode depends at least in part on the load imposed by the competing activities.

The results in studies of divided attention are generally compatible with a view of attention, or effort, as an input to central structures which enables or facilitates their operation. The main attributes of attention are the following:

(*1*) Attention is limited, but the limit is variable from moment to moment. Physiological indices of arousal provide a measure that is correlated to the momentary limit.

(*2*) The amount of attention or effort exerted at any time depends primarily on the demands of current activities. While the investment of attention increases with demands, the increase is typically insufficient to fully compensate for the effects of increased task complexity.

(*3*) Attention is divisible. The allocation of attention is a matter of degree. At high levels of task load, however, attention becomes more nearly unitary.

(*4*) Attention is selective, or controllable. It can be allocated to facilitate the processing of selected perceptual units or the execution of selected units of performance. The policy of allocation reflects permanent dispositions and temporary intentions.

REVIEW

This final chapter applied the theory of effort introduced in Chapter 2 to the interpretation of task interference. There is strong experimental support for the main conclusion from this theory, that interference between concurrent tasks depends on the demands that these tasks separately impose on the limited capacity system. The effort demands of tasks do not always correspond to intuitive notions of task difficulty. For example, subvocal rehearsal, the choice and execution of free responses, and tests of recall on familiar material appear to require considerable effort, although they would be judged simple.

The spare capacity which is available at any instant during the performance of a primary task can be measured by the accuracy and speed with which unexpected probe signals are handled.

A distinction was drawn between two meanings of the term attention demands. Demand_1 denotes that an activity cannot be carried out without a sufficient allocation of attention. Demand_2 denotes that a prior selective set or an evaluation of the quality of performance of an activity controls the amount and allocation of attention. Perceptual analysis normally does not demand_2 attention, although it demands_1 attention. These terms were applied to an analysis of several variants of preparatory set, of which some reduce the attentional requirements of tasks, while others ensure that these requirements will be met.

Some evidence for structural interference was reviewed. There appear to be many situations in which concurrent tasks interact so that the demands of dual performance greatly exceed what would be expected on the hypothesis that effort is additive. Structural interference is typically observed when the interacting tasks require the operation of similar mechanisms of perception or response.

The final section reviewed the interpretation of interference within an effort theory. The concept that interference occurs only when a limited capacity is exceeded was rejected, because capacity appears to be variable, and because interference arises even among fairly undemanding tasks. Interference was explained on the alternative assumption that the supply of attention generally fails to meet increasing demands. This assumption is needed to explain why increased effort fails to compensate fully for increased difficulty, in both the single-task and dual-task situations.

References

ADAMS, J. A. (1962) Test of the hypothesis of psychological refractory period. *Journal of Experimental Psychology, 64,* 280–287.

———. (1966) Some mechanisms of motor responding: An examination of attention. In *Acquisition of skills,* ed. E. A. Bilodeau. New York: Academic Press. Pp. 169–200.

AGNEW, N., and AGNEW, M. (1963) Drive level effects on tasks of narrow and broad attention. *Quarterly Journal of Experimental Psychology, 15,* 58–62.

ALLPORT, D. A. (1971) Parallel encoding within and between elementary stimulus dimensions. *Perception and Psychophysics, 10,* 104–108.

———, ANTONIS, B., and REYNOLDS, P. (1972) On the division of attention: A disproof of the single channel hypothesis. *Quarterly Journal of Experimental Psychology, 24,* 225–235.

ALPERN, M. (1971) Effector mechanisms in vision. In *Experimental Psychology,* eds. J. W. Kling and L. A. Riggs. New York: Holt, Rinehart & Winston.

AMADEO, M., and GOMEZ, E. (1966) Eye movements, attention and dreaming in subjects with life-long blindness. *Canadian Psychiatric Association Journal, 11,* 501–507.

ANTROBUS, J. S., ANTROBUS, J. S., and SINGER, J. L. (1964) Eye movements accompanying daydreaming, visual imagery, and thought suppression. *Journal of Abnormal and Social Psychology, 69,* 244–252.

ARCHER, E. J. (1962) Concept identification as a function of obviousness of relevant and irrelevant information. *Journal of Experimental Psychology, 63,* 616–620.

ARGYLE, M., and DEAN, J. (1965) Eye-contact, distance and affiliation. *Sociometry, 28,* 289–304.

ATKINSON, R. C., and SHIFFRIN, R. M. (1968) Human memory: a proposed system and its control processes. In *The Psychology of Learning and Motivation: Advances in Research and Theory,* Vol. II., New York: Academic Press., Pp. 89–195.

ATTNEAVE, F. (1959) *Applications of information theory to psychology: A summary of basic concepts, methods and results.* New York: Holt, Rinehart & Winston.

AVERBACH, E., and CORIELL, A. S. (1961) Short-term memory in vision. *Bell System Technical Journal, 40,* 309–328.

———, and SPERLING, G. (1961) Short-term storage of information in vision. In *Information theory–Fourth London symposium,* ed. E. C. Cherry. London: Butterworths. Pp. 196–211.

AVNER, U. (1972) Interdependence between right and left ear in processing simultaneous items as function of attentional intensity. Master's thesis, Hebrew University, Jerusalem. (Hebrew)

AXELROD, S., and GUZY, L. T. (1968) Underestimation of dichotic click rates: Results using methods of absolute estimation and constant stimuli. *Psychonomic Science, 12,* 133–134.

———, GUZY, L. T., and DIAMOND, I. T. (1968) Perceived rate of monotic and dichotically alternating clicks. *Journal of the Acoustical Society of America, 43,* 51–55.

———, and POWAZEK, M. (1972) Dependence of apparent rate of alternating clicks on azimuthal separation between sources. *Psychonomic Science, 26,* 217–218.

BADDELEY, A. D. (1966) The capacity for generating information by randomization. *Quarterly Journal of Experimental Psychology, 18,* 119–129.

———, HATTER, J. E., SCOTT, D., and SNASHALL, A. (1970) Memory and the time of day. *Quarterly Journal of Experimental Psychology, 22,* 605–609.

———, SCOTT, D., DRYNAN, R., and SMITH, J. C. (1969) Short-term memory and the limited capacity hypothesis. *British Journal of Psychology, 60,* 51–55.

BADIA, P., and DEFRAN, R. H. (1970) Orienting responses and GSR conditioning: A dilemma. *Psychological Review, 77,* 171–181.

BAHRICK, H. P., FITTS, P. M., and RANKIN, R. E. (1952) Effect of incentives upon reactions to peripheral stimuli. *Journal of Experimental Psychology, 44,* 400–406.

———, and SHELLY, C. (1958) Time-sharing as an index of automatization. *Journal of Experimental Psychology, 56,* 288–293.

BAKAN, P. (1971) The eyes have it. *Psychology Today, 4,* (11), 64–67, 96.

———, BELTON, J. A., and TOTH, J. C. (1963) Extraversion-introversion and decrement in an auditory vigilance task. In *Vigilance: A symposium,* eds. D. N. Buckner and J. J. McGrath. New York: McGraw-Hill. Pp. 22–28.

———, and LECKART, B. T. (1966) Attention, extraversion, and stimulus-personality congruence. *Perception and Psychophysics, 1,* 355–357.

———, and SHOTLAND, R. L. (1969) Lateral eye movement, reading speed, and visual attention. *Psychonomic Science, 15,* 93–94.

BARTZ, D. H., SATZ, P., and FENNELL, E. (1967) Grouping strategies in dichotic listening: The effects of instructions, rate, and ear asymmetry. *Journal of Experimental Psychology, 74,* 132–136.

BEATTY, J., and KAHNEMAN, D. (1966) Pupillary changes in two memory tasks. *Psychonomic Science, 5,* 371–372.

BECK, J. (1966) Effect of orientation and of shape similarity on perceptual grouping. *Perception and Psychophysics, 1,* 300–302.

———. (1967) Perceptual grouping produced by line figures. *Perception and Psychophysics, 2,* 491–495.

———. (1972) Similarity grouping and peripheral discriminability under uncertainty. *American Journal of Psychology, 85,* 1–19.

———, and AMBLER, B. (1972) Discriminability of differences in line-slope and in line-arrangement as a function of mask delay. *Perception and Psychophysics, 12,* 33–38.

BERKSON, G. (1965) Eye fixation responses to one or two stimuli. *Journal of Comparative and Physiological Psychology, 59,* 422–425.

BERLYNE, D. E. (1950) Stimulus intensity and attention in relation to learning theory. *Quarterly Journal of Experimental Psychology, 2,* 71–75.

———. (1951) Attention to change. *British Journal of Psychology, 42,* 269–278.

———. (1957) Conflict and information-theory variables as determinants of human perceptual curiosity. *Journal of Experimental Psychology, 53,* 399–404.

———. (1958) The influence of complexity and novelty in visual figures on orienting responses. *Journal of Experimental Psychology, 55,* 289–296.

———. (1960) *Conflict, arousal and curiosity.* New York: McGraw-Hill.

———. (1965) *Structure and direction in thinking.* New York: John Wiley.

———. (1966) Curiosity and exploration. *Science, 153,* 25–33.

———. (1967) Arousal and reinforcement. In *Nebraska symposium on motivation,* ed. D. Levine. Lincoln: University of Nebraska Press. Pp. 1–110.

———. (1970) Attention as a problem in behavior theory. In *Attention: Contemporary theory and analysis,* ed. D. E. Mostofsky. New York: Appleton-Century-Crofts. Pp. 25–49.

———, and Borsa, D. M. (1968) Uncertainty and the orientation reaction. *Perception and Psychophysics, 3,* 77–79.

———, Borsa, D. M., Craw, M. A., Gelman, R. S., and Mandell, E. E. (1965) Effects of stimulus complexity and induced arousal on paired-associate learning. *Journal of Verbal Learning and Verbal Behavior, 4,* 291–299.

———, Borsa, D. M., Hamacher, J. H., and Koenig, I. D. (1966) Paired-associate learning and the timing of arousal. *Journal of Experimental Psychology, 72,* 1–6.

———, and Carey, S. T. (1968) Incidental learning and the timing of arousal. *Psychonomic Science, 13,* 103–104.

———, and Lawrence, G. H. (1964) Effects of complexity and incongruity variables on GSR, investigatory behavior and verbally expressed preference. *Journal of General Psychology, 71,* 21–45.

———, and McDonnell, P. (1965) Effects of stimulus complexity and incongruity on duration of EEG desynchronization. *EEG and Clinical Neurophysiology, 18,* 156–161.

Bernstein, A. S. (1969) To what does the orienting response respond? *Psychophysiology, 6,* 338–350.

———, Taylor, K., Austen, B. G., Nathanson, M., and Scarpelli, A. (1971) Orienting response and apparent movement toward or away from the observer. *Journal of Experimental Psychology, 87,* 37–45.

Bernstein, I. H. (1970) Can we see and hear at the same time? Some recent studies of intersensory facilitation of reaction time. *Acta Psychologica, 33, Attention and performance III,* ed. A. F. Sanders. Amsterdam: North-Holland Publishing Co. Pp. 21–35.

———, Clark, M. H., and Edelstein, B. A. (1969a) Effects of an auditory signal on visual reaction time. *Journal of Experimental Psychology, 80,* 567–569.

———, Clark, M. H., and Edelstein, B. A. (1969b) Intermodal effects in choice reaction time. *Journal of Experimental Psychology, 81,* 405–407.

Bertelson, P. (1966) Central intermittency twenty years later. *Quarterly Journal of Experimental Psychology, 18,* 153–163.

———. (1967) The refractory period of choice reactions with regular and irregular interstimuli intervals. *Acta Psychologica, 27,* 45–56.

———, and Tisseyre, F. (1969) The time-course of preparation: Confirmatory results with visual and auditory warning signals. *Acta Psychologica, 30, Attention and performance II,* ed. W. G. Koster, 145–154.

Biederman, I. (1972) Human performance in contingent information-processing tasks. *Journal of Experimental Psychology, 93,* 219–238.

———, and Checkosky, S. F. (1970) Processing redundant information. *Journal of Experimental Psychology, 83,* 486–490.

Blake, M. J. F. (1967) Time of day effects on performance in a range of tasks. *Psychonomic Science, 9,* 349–350.

Blake, R. R., and Fox, R. (1969) Visual form recognition threshold and the psychological refractory period. *Perception and Psychophysics, 5,* 46–48.

Boggs, D. H., and Simon, J. R. (1968) Differential effect of noise on tasks of varying complexity. *Journal of Applied Psychology, 52,* 148–153.

Borger, R. (1963) The refractory period and serial choice-reactions. *Quarterly Journal of Experimental Psychology, 15,* 1–12.

Boring, E. G. (1950) *A history of experimental psychology* (2nd ed.). New York: Appleton-Century-Crofts.

Bradshaw, J. L. (1968a) Load and pupillary changes in continuous processing tasks. *British Journal of Psychology, 59,* 265–271.

———. (1968b) Pupil size and problem solving. *Quarterly Journal of Experimental Psychology, 20,* 116–122.

Brand, J. (1971) Classification without identification in visual search. *Quarterly Journal of Experimental Psychology, 23,* 178–186.

Broadbent, D. E. (1952) Listening to one of two synchronous messages. *Journal of Experimental Psychology, 44,* 51–55.

———. (1954a) The role of auditory localization in attention and memory span. *Journal of Experimental Psychology, 47,* 191–196.

———. (1954b) Some effects of noise on visual performance. *Quarterly Journal of Experimental Psychology, 6,* 1–5.

———. (1956) Listening between and during practiced auditory distraction. *British Journal of Psychology, 47,* 51–60.

———. (1957a) A mechanical model for human attention and immediate memory. *Psychological Review, 64,* 205–215.

———. (1957b) Effects of noise on behavior. In *Handbook of noise control,* ed. C. M. Harris. New York: McGraw-Hill. Pp. 1–33.

———. (1958) *Perception and communication.* London: Pergamon Press Ltd.

———. (1963) Possibilities and difficulties in the concept of arousal. In *Vigilance: A symposium,* eds. D. N. Buckner and J. J. McGrath. New York: McGraw-Hill. Pp. 184–198.

———. (1967) Word-frequency effect and response bias. *Psychological Review, 74,* 1–15.

———. (1970) Stimulus set and response set: Two kinds of selective attention. In *Attention: Contemporary theories and analysis,* ed. D. I. Mostofsky. New York: Appleton-Century-Crofts. Pp. 51–60.

———. (1971) *Decision and stress.* London: Academic Press.

———, and Gregory, M. (1961) On the recall of stimuli presented alternately to two sense organs. *Quarterly Journal of Experimental Psychology, 13,* 103–109.

———, and Gregory, M. (1963) Division of attention and the decision theory of signal detection. *Proceedings of the Royal Society,* B, *158,* 222–231.

———, and Gregory, M. (1964) Stimulus set and response set: The alternation of attention. *Quarterly Journal of Experimental Psychology, 16,* 309–317.

———, and GREGORY, M. (1965) Some confirmatory results on age differences in memory for simultaneous stimulation. *British Journal of Psychology, 56,* 77–80.

———, and GREGORY, M. (1967) Psychological refractory period and the length of time required to make a decision. *Proceedings of the Royal Society,* B, *168,* 181–193.

———, and HERON, A. (1962) Effects of a subsidiary task on performance involving immediate memory by younger and older men. *British Journal of Psychology, 53,* 189–198.

BROADHURST, P. L. (1957) Emotionality and the Yerkes-Dodson law. *Journal of Experimental Psychology, 54,* 345–352.

———. (1959) The interaction of task difficulty and motivation: The Yerkes-Dodson law revived. *Acta Psychologica, 16,* 321–338.

BROOKS, L. R. (1967) The suppression of visualization by reading. *Quarterly Journal of Experimental Psychology, 19,* 289–299.

———. (1968) Spatial and verbal components of the act of recall. *Canadian Journal of Psychology/Review of Canadian Psychology, 22,* 349–368.

———. (1970) An extension of the conflict between visualization and reading. *Quarterly Journal of Experimental Psychology, 22,* 91–96.

BROWN, C. R., and RUBENSTEIN, H. (1961) Test of response bias explanation of word-frequency. *Science, 133,* 280–281.

BROWN, I. D. (1964) The measurement of perceptual load and reserve capacity. *Transactions of the Association of Industrial Medical Officers, 14,* 44–49.

———. (1966) Measuring the difficulty of perceptual-motor tasks: Some limitations to dual-task techniques. Paper presented to the Ergonomics Research Society, Annual Conference.

———. (1968) Criticisms of time-sharing techniques for the measurement of perceptual-motor difficulty. *XVI International Congress of Applied Psychology.* Amsterdam: Swets & Zeitlinger. Pp. 322–328.

———, SIMMONS, D. C., and TICKNER, A. H. (1967) Measurement of control skills, vigilance, and performance on a subsidiary task during 12 hours of car driving. *Ergonomics, 10,* 665–673.

BROWN, J. (1970) Recognition and the direction of attention. *Acta Psychologica, 33,* 149–157.

BROWN, L. T., and FARHA, W. (1966) Some physical determinants of viewing time under three instructional sets. *Perception and Psychophysics, 1,* 2–4.

———, and GREGORY, L. P. (1968) Attentional response of humans and squirrel monkeys to visual patterns: Final studies and resumé. *Perceptual and Motor Skills, 27,* 787–814.

BRUNER, J. S. (1957) On perceptual readiness. *Psychological Review, 64,* 123–152.

BRYDEN, M. P. (1961) The role of post-exposural eye movements in tachistoscopic perception. *Canadian Journal of Psychology, 15,* 220–225.

———. (1962) Order of report in dichotic listening. *Canadian Journal of Psychology, 16,* 291–299.

———. (1964) The manipulation of strategies of report in dichotic listening. *Canadian Journal of Psychology, 18,* 126–138.

———. (1971) Attentional strategies and short-term memory in dichotic listening. *Cognitive Psychology, 2,* 99–116.

BURSILL, A. E. (1958) The restriction of peripheral vision during exposure to hot and humid conditions. *Quarterly Journal of Experimental Psychology, 10,* 113–129.

CALLAWAY, E. (1959) The influence of amobarbital (amylobarbitone) and methamphetamine on the focus of attention. *Journal of Mental Science, 105,* 382–392.

———, and STONE, G. (1960) Re-evaluating the focus of attention. In *Drugs and behavior,* eds. L. Uhr and J. G. Miller. New York: John Wiley. Pp. 393–398.

———, and THOMPSON, S. V. (1953) Sympathetic activity and perception: An approach to the relationships between autonomic activity and personality. *Psychosomatic Medicine, 15,* 443–455.

CAMPOS, J. J., and JOHNSON, H. J. (1966) The effects of verbalization instructions and visual attention on heart rate and skin conductance. *Psychophysiology, 2,* 305–310.

———, and JOHNSON, H. J. (1967) Affect, verbalization, and directional fractionation of autonomic responses. *Psychophysiology, 3,* 285–290.

CARVER, R. P. (1971) Pupil dilation and its relationship to information processing during reading and listening. *Journal of Applied Psychology, 55,* 126–134.

CATLIN, J. (1969) On the word-frequency effect. *Psychological Review, 76,* 504–506.

CAVANAGH, J. P., and CHASE, W. G. (1971) The equivalence of target and nontarget processing in visual search. *Perception and Psychophysics, 9,* 493–495.

CHASE, W. G., GRAHAM, F. K., and GRAHAM, D. T. (1968) Components of HR response in anticipation of reaction time and exercise tasks. *Journal of Experimental Psychology, 76,* 642–648.

CHERRY, E. C. (1953) Some experiments on the recognition of speech, with one and two ears. *Journal of the Acoustical Society of America, 25,* 975–979.

———. (1957) *On human communication: A review, a survey, and a criticism.* Cambridge: Technology Press, MIT; New York: John Wiley.

———, and TAYLOR, W. K. (1954) Some further experiments upon the recognition of speech with one and two ears. *Journal of the Acoustical Society of America, 26,* 554–559.

COHEN, J. (1969) Very slow brain potentials relating to expectancy: The CNV. In *Average evoked potentials: Methods, results, and evaluations,* eds. E. Donchin and D. B. Lindsley. NASA, SP–191, Washington, D.C. Pp. 143–198.

COHEN, M. J., and JOHNSON, H. J. (1971) Relationship between heart rate and muscular activity within a classical conditioning paradigm. *Journal of Experimental Psychology, 90,* 222–226.

COLAVITA, F. B. (1971) Interspecies differences in sensory dominance. Paper presented at the Twelfth Annual Meeting of the Psychonomic Society, St. Louis, Missouri, November.

COLMAN, F. D., and PAIVIO, A. (1969) Pupillary response and galvanic skin response during an imagery task. *Psychonomic Science, 16,* 296–297.

———, and PAIVIO, A. (1970) Pupillary dilation and mediation process during paired-associate learning. *Canadian Journal of Psychology, 24,* 261–270.

CONNOR, W. H., and LANG, P. J. (1969) Cortical slow-wave and cardiac-rate responses in stimulus orientation and RT conditions. *Journal of Experimental Psychology, 82,* 310–320.

COOMBS, C. H., DAWES, R. M., and TVERSKY, A. (1970) *Mathematical psychology: An elementary introduction.* Englewood Cliffs, N.J.: Prentice-Hall.

COQUERY, J. M., and LACEY, J. I. (1966) The effects of foreperiod duration on the components of the cardiac response during the foreperiod of a reaction-time experiment. Paper presented at the Meeting of the Society for Psychophysiological Research, Denver, October.

CORBALLIS, M. C., and LUTHE, L. (1971) Two-channel visual memory. *Perception and Psychophysics, 9,* 361–367.

CORCORAN, D. W. J. (1965) Personality and the inverted-U relation. *British Journal of Psychology, 56,* 267–273.

CORNSWEET, D. J. (1969) Use of cues in the visual periphery under conditions of arousal. *Journal of Experimental Psychology, 80,* 14–18.

CORTEEN, R. S. (1969) Skin conductance changes and word recall. *British Journal of Psychology, 60,* 81–84.

———, and WOOD, B. (1972) Autonomic responses to shock-associated words in an unattended channel. *Journal of Experimental Psychology, 94,* 308–313.

CRAFT, J. L., and SIMON, J. R. (1970) Processing symbolic information from a visual display: Interference from an irrelevant directional cue. *Journal of Experimental Psychology, 83,* 415–420.

CRAIK, K. J. W. (1947) Theory of the human operator in control systems I. The operator as an engineering system. *British Journal of Psychology, 38,* 56–61.

———. (1948) Theory of the human operator in control systems II. Man as an element in a control system. *British Journal of Psychology, 38,* 142–148.

CREAMER, L. R. (1963) Event uncertainty, psychological refractory period, and human data processing. *Journal of Experimental Psychology, 66,* 187–194.

CROVITZ, H. F., and DAVES, W. (1962) Tendencies to eye movement and perceptual accuracy. *Journal of Experimental Psychology, 63,* 495–498.

CROWDER, R. G. (1967) Prefix effects in immediate memory. *Canadian Journal of Psychology, 21,* 450–461.

———. (1969) Phonic interference and the prefix effect. *Journal of Verbal Learning and Verbal Behavior, 8,* 302–321.

———. (1971) Waiting for the stimulus suffix: Decay, delay, rhythm, and readout in immediate memory. *Quarterly Journal of Experimental Psychology, 23,* 324–340.

———, and MORTON, J. (1969) Precategorical acoustic storage (PAS). *Perception and Psychophysics, 5,* 365–373.

DALLETT, K. M. (1964) Effects of a supplementary prefix on recall. *Journal of Experimental Psychology, 67,* 296–298.

DAVIES, D. R. (1968) Physiological and psychological effects of exposure to high intensity noise. *Applied Acoustics, 1,* 215–233.

———, and HOCKEY, G. R. J. (1966) The effects of noise and doubling the signal frequency on individual differences in visual vigilance performance. *British Journal of Psychology, 57,* 381–389.

———, and TAYLOR, A. (1969) Varied auditory stimulation, temperament differences and vigilance performance. *British Journal of Psychology, 60,* 453–457.

DAVIS, R. (1957) The human operator as a single channel information system. *Quarterly Journal of Experimental Psychology,* 9, 119–129.

———. (1959) The role of "attention" in the psychological refractory period. *Quarterly Journal of Experimental Psychology, 11,* 211–220.

———. (1962) Choice reaction times and the theory of intermittency in human performance. *Quarterly Journal of Experimental Psychology, 14,* 157–166.

DAVIS, R. C. (1957) Response patterns. *Transactions of the New York Academy of Sciences,* series 2, *19,* 731–737.

DAY, H. (1965) Exploratory behavior as a function of individual differences and level of arousal. Ph.D. dissertation, University of Toronto.

———. (1966) Looking time as a function of stimulus variables and individual differences. *Perceptual and Motor Skills, 22,* 423–428.

DAY, M. E. (1964) An eye movement phenomenon relating to attention, thought and anxiety. *Perceptual and Motor Skills, 19,* 443–446.

———. (1967a) An eye-movement indicator of type and level of anxiety: Some clinical observations. *Journal of Clinical Psychology, 23,* 438–441.

———. (1967b) An eye movement indicator of individual differences in the physiological organization of attentional processes and anxiety. *Journal of Psychology, 66,* 51–62.

DEANE, G. E. (1961) Human heart rate responses during experimentally induced anxiety. *Journal of Experimental Psychology, 61,* 489–493.

DE GROOT, A. D. (1966) Perception and memory versus thought: Some old ideas and recent findings. In *Problem solving: Research, method, and theory,* ed. B. Kleinmuntz. New York: John Wiley.

DEUTSCH, J. A., and DEUTSCH, D. (1963) Attention: Some theoretical considerations. *Psychological Review, 70,* 80–90.

———, and DEUTSCH, D. (1967) Comments on "Selective attention: Perception or response?" *Quarterly Journal of Experimental Psychology, 19,* 362–363.

DILLON, R. F., and REID, L. S. (1969) Short-term memory as a function of information processing during the retention interval. *Journal of Experimental Psychology, 81,* 261–269.

DIMOND, S. (1970) Reaction times and response competition between the right and left hands. *Quarterly Journal of Experimental Psychology, 22,* 513–520.

DUFFY, E. (1957) The psychological significance of the concept of "arousal" or "activation." *Psychological Review, 64,* 265–275.

DURHAM, R. L., NUNNALLY, J. C., and LEMOND, L. C. (1971) The effects of levels of information conflict on visual selection. *Perception and Psychophysics, 10,* 93–96.

EASON, R. G. (1963) Relation between effort, tension level, skill, and performance efficiency in a perceptual-motor task. *Perceptual and Motor Skills, 16,* 297–317.

EASTERBROOK, J. A. (1959) The effect of emotion on cue utilization and the organization of behavior. *Psychological Review, 66,* 183–201.

EGETH, H. E. (1967) Selective attention. *Psychological Bulletin, 67,* 41–57.

———, BLECKER, D. L., and KAMLET, A. S. (1969) Verbal interference in a perceptual comparison task. *Perception and Psychophysics, 6,* 355–356.

———, and PACHELLA, R. (1969) Multidimensional stimulus identification. *Perception and Psychophysics, 5,* 341–346.

EISLER, H., and KNOPPEL, J. K. (1970) Relative attention in judgments of heterogeneous similarity. *Perception and Psychophysics, 8,* 420–426.

ELITHORN, A. (1961) Central intermittency: Some further observations. *Quarterly Journal of Experimental Psychology, 13,* 240–247.

———, and LAWRENCE, C. (1955) Central inhibition: Some refractory observations. *Quarterly Journal of Experimental Psychology, 7,* 116–127.

ELLIOTT, R. (1969) Tonic heart rate: Experiments on the effects of collative variables lead to a hypothesis about its motivational significance. *Journal of Personality and Social Psychology, 12,* 211–228.

———, BANKART, B., and LIGHT, R. (1970) Differences in the motivational significance of heart rate and palmar conductance: Two tests of a hypothesis. *Journal of Personality and Social Psychology, 14,* 166–172.

ELLIS, S. H. and CHASE, W. G. (1971) Parallel processing in item recognition. *Perception and Psychophysics, 10,* 379–384.

ELLS, J. (1969) Attention requirements of movement control. Unpublished Ph. D. dissertation, University of Oregon.

EPSTEIN, W., and ROCK, I. (1960) Perceptual set as an artifact of recency. *American Journal of Psychology, 73,* 214–228.

ERIKSEN, C. W., and COLLINS, J. F. (1969a) Visual perception rate under two conditions of search. *Journal of Experimental Psychology, 80,* 489–492.

———, and COLLINS, J. F. (1969b) Temporal course of selective attention. *Journal of Experimental Psychology, 80,* 254–261.

———, and HOFFMAN, J. E. (1972) Some characteristics of selective attention in visual perception determined by vocal reaction time. *Perception and Psychophysics, 11,* 169–171.

———, and LAPPIN, J. S. (1967) Selective attention and very short-term recognition memory for nonsense forms. *Journal of Experimental Psychology, 73,* 358–364.

———, and ROHRBAUGH, J. W. (1970) Some factors determining efficiency of selective attention. *American Journal of Psychology, 83,* 330–342.

EXLINE, R. V. (1963) Exploration in the process of person perception: Visual interaction in response to competition, sex and need for affiliation. *Journal of Personality, 31,* 1–20.

———. (1971) Visual interaction: The glances of power and preference. In *Nebraska symposium on motivation,* ed. J. K. Cole. Lincoln: University of Nebraska Press. Pp. 163–206.

EYSENCK, H. J. (1967) *The biological basis of personality.* Springfield, Ill.: Charles C. Thomas.

———, and THOMPSON, W. (1966) The effects of distraction on pursuit rotor learning, performance and reminiscence. *British Journal of Psychology, 57,* 99–106.

FANTZ, R. L. (1958) Pattern vision in young infants. *Psychological Record, 8,* 43–47.

———. (1965a) Visual perception from birth as shown by pattern selectivity. *Annals of the New York Academy of Sciences, 118,* 793–814.

———. (1965b) The ontogeny of perception. In *Behavior of non-human primates,* eds. A. M. Schrier, H. F. Harlow, and F. Stolhitz. New York: Academic Press. Pp. 365–463.

———. (1967) Visual perception and experience in early infancy: A look at the hidden side of behavior development. In *Early behavior: Comparative and developmental approaches,* eds. H. W. Stevenson, E. H. Hess, and H. L. Rheingold. New York: John Wiley.

FEHRER, E., and RAAB, D. (1962) Reaction time to stimuli masked by metacontrast. *Journal of Experimental Psychology, 63,* 143–147.

FELFOLDY, G. L., and GARNER, W. R. (1971) The effects on speeded classification of implicit and explicit instructions regarding redundant dimensions. *Perception and Psychophysics, 9,* 289–292.

FELLOWS, B. J. (1968) *The discrimination process and development.* Oxford: Pergamon Press.

FITTS, P. M., and BIEDERMAN, I. (1965) S-R compatibility and information reduction. *Journal of Experimental Psychology, 69,* 408–412.

———, and POSNER, M. I. (1967) *Human performance.* Belmont, Calif.: Brooks Cole Publishing Co.

FODOR, J. A., and BEVER, T. G. (1965) The psychological reality of linguistic segments. *Journal of Verbal Learning and Verbal Behavior, 4,* 414–420.

FOX, L. A., SHOR, R. E., and STEINMAN, R. J. (1971) Semantic gradients and interference in naming color, spatial direction, and numerosity. *Journal of Experimental Psychology, 91,* 59–65.

FRAISSE, P. (1957) La periode refractaire psychologique. *Année Psychologique, 57,* 315–328.

———, EHRLICH, S., and VURPILLOT, E. (1956) Etudes de la centration perceptive par la methode tachistoscopique. *Archives de Psychologie Geneve, 35,* 193–214.

FREUD, S. (1900) The interpretation of dreams. (Original German ed., New York: Basic Books, 1955).

FUREDY, J. J., and SCULL, J. (1971) Orienting-reaction theory and an increase in the human GSR following stimulus change which is unpredictable but not contrary to prediction. *Journal of Experimental Psychology, 88,* 292–294.

FURST, C. J. (1971) Automatizing of visual attention. *Perception and Psychophysics, 10,* 65–70.

GARNER, W. R. (1962) *Uncertainty and structure as psychological concepts.* New York: John Wiley.

———. (1970) The stimulus in information processing. *American Psychologist, 25,* 350–358.

———, and FELFOLDY, G. L. (1970) Integrality of stimulus dimensions in various types of information processing. *Cognitive Psychology, 1,* 225–241.

GARVEY, W. D., and TAYLOR, F. V. (1959) Interactions among operator variables, system dynamics, and task-induced stress. *Journal of Applied Psychology, 43,* 79–85.

GERMANA, J. (1968) Response characteristics and the orienting reflex. *Journal of Experimental Psychology, 78,* 610–616.

GESELL, A., and ILG, F. L. (1949) *Child development: An introduction to the study of human growth.* New York: Harper & Row.

GIBSON, E. J. (1965) Learning to read. *Science, 148,* 1066–1072.

———. (1969) *Principles of perceptual learning and development.* New York: Appleton-Century-Crofts.

GIBSON, J. J., and PICK, A. D. (1963) Perception of another person's looking behavior. *American Journal of Psychology, 76,* 386–394.

GOLDWATER, B. C. (1972) Psychological significance of pupillary movements. *Psychological Bulletin, 77,* 340–355.

GOODWIN, W. R., and LAWRENCE, D. H. (1955) The functional independence of two discrimination habits associated with a constant stimulus situation. *Journal of Comparative and Physiological Psychology, 48,* 437–443.

GOPHER, D. (1971) Patterns of eye movement in auditory tasks of selective attention. Unpublished Ph.D. thesis, Hebrew University, Jerusalem. (Hebrew)

———, and KAHNEMAN, D. (1971) Individual differences in attention and the prediction of flight criteria. *Perceptual and Motor Skills, 33,* 1335–1342.

GORDON, I. E. (1969) Eye movements during search through printed lists. *Perceptual and Motor Skills, 29,* 683–686.

———, DULEWICZ, V., and WINWOOD, M. (1971) Irrelevant item variety and visual search. *Journal of Experimental Psychology, 88,* 295–296.

GOTTSDANKER, R. (1969) Interacting responses to crowded signals. *Acta Psychologica, 30,* 168–176.

———, BROADBENT, L., and VAN SANT, C. (1963) Reaction time to single and to first signals. *Journal of Experimental Psychology, 66,* 163–167.

GOTTWALD, R. L., and GARNER, W. R. (1972) Effects of focusing strategy on speeded classification with grouping, filtering, and condensation tasks. *Perception and Psychophysics, 11,* 179–182.

GOULD, J. D. (1967) Pattern recognition and eye-movement parameters. *Perception and Psychophysics, 2,* 399–407.

———, and DILL, A. B. (1969) Eye-movement parameters and pattern discrimination. *Perception and Psychophysics, 6,* 311–320.

———, and PEEPLES, D. R. (1970) Eye movements during visual search and discrimination of meaningless, symbol, and object patterns. *Journal of Experimental Psychology, 85,* 51–55.

———, and SCHAFFER, A. (1965) Eye-movement patterns in scanning numeric displays. *Perceptual Motor Skills, 20,* 521–535.

GRAHAM, F. K., and CLIFTON, R. K. (1966) Heart-rate change as a component of the orienting response. *Psychological Bulletin, 65,* 305–320.

GRAY, J. A., and WEDDERBURN, A. A. I. (1960) Grouping strategies with simultaneous stimuli. *Quarterly Journal of Experimental Psychology, 12,* 180–184.

GREEN, D. M., and SWETS, J. A. (1966) *Signal detection theory and psychophysics.* New York: John Wiley.

GREENWALD, A. G. (1970a) A double stimulation test of ideomotor theory with implications for selective attention. *Journal of Experimental Psychology, 84,* 392–398.

———. (1970b) Selective attention as a function of signal rate. *Journal of Experimental Psychology, 86,* 48–52.

———. (1970c) Sensory feedback mechanisms in performance control: With special reference to the ideo-motor mechanism. *Psychological Review, 77,* 73–100.

GRINDLEY, G. C., and TOWNSEND, V. (1968) Voluntary attention in peripheral vision and its effects on acuity and differential thresholds. *Quarterly Journal of Experimental Psychology, 20,* 11–19.

HABER, R. N. (1964a) A replication of selective attention and coding in visual perception. *Journal of Experimental Psychology, 67,* 402–404.

———. (1964b) Effects of coding strategy on perceptual memory. *Journal of Experimental Psychology, 68,* 357–362.

———. (1966) Nature of the effect of set on perception. *Psychological Review, 73,* 335–351.

HAKEREM, G., and SUTTON, S. (1966) Pupillary response at visual threshold. *Nature, 212,* 485–486.

HARRIS, C. S., and HABER, R. N. (1963) Selective attention and coding in visual perception. *Journal of Experimental Psychology, 65,* 328–333.

HASTINGS, S. E., and OBRIST, P. A. (1967) Heart rate during conditioning in humans: Effect of varying the interstimulus (CS-UCS) interval. *Journal of Experimental Psychology, 74,* 431–442.

HAWKINS, H. L. (1969) Parallel processing in complex visual discrimination. *Perception and Psychophysics, 5,* 56–64.

HEIDER, F., and SIMMEL, M. (1944) An experimental study of apparent behavior. *American Journal of Psychology, 57,* 243–259.

HELD, R. (1968) Dissociation of visual functions by deprivation and rearrangement. *Psychologische Forschung, 31,* 338–348.

HENIK, A. (1972) Intrusions in dichotic listening. Unpublished M. A. thesis, Hebrew University, Jerusalem. (Hebrew)

HERMAN, L. M. (1969) Effects of second signals on response time to first signals under certainty and uncertainty. *Journal of Experimental Psychology, 80,* 106–112.

———, and KANTOWITZ, B. H. (1970) The psychological refractory period effect: Only half the double-stimulation story? *Psychological Bulletin, 73,* 74–88.

———, and MCCAULEY, M. E. (1969) Delay in responding to the first stimulus in the "psychological refractory period" experiment: Comparisons with delay produced by a second stimulus not requiring a response. *Journal of Experimental Psychology, 81,* 344–350.

HERNANDEZ-PEON, R. (1964) Psychiatric implications of neurophysiological research. *Bulletin of the Menninger Clinic, 28,* 165–185.

HERSHENSON, M., MUNSINGER, H., and KESSEN, W. (1965) Preference for shapes of intermediate variability in the newborn human. *Science, 147,* 630–631.

HESS, E. H. (1965) Attitude and pupil size. *Scientific American, 212,* 46–54.

———, and POLT, J. M. (1964) Pupil size in relation to mental activity during simple problem-solving. *Science, 143,* 1190–1192.

HILLYARD, S. A. (1969) Relationships between the contingent negative variation (CNV) and reaction time. *Physiology and Behavior, 4,* 351–357.

HINTZMAN, D. L., CARRE, F. A., ESKRIDGE, V. L., OWENS, A. M., SHAFF, S. S., and SPARKS, M. E. (1972) "Stroop" effect: Input or output phenomenon? *Journal of Experimental Psychology, 95,* 458–459.

HOCHBERG, J. E. (1970) Attention, organization, and consciousness. In *Atten-*

tion: Contemporary theory and analysis, ed. D. I. Mostofsky. New York: Appleton-Century-Crofts. Pp. 99–124.

HOCKEY, G. R. J. (1969) Noise and efficiency: The visual task. *New Scientist, 42,* 244–246.

———. (1970a) Effect of loud noise on attentional selectivity. *Quarterly Journal of Experimental Psychology, 22,* 28–36.

———. (1970b) Signal probability and spatial location as possible bases for increased selectivity in noise. *Quarterly Journal of Experimental Psychology, 22,* 37–42.

———. (1970c) Changes in attention allocation in a multicomponent task under loss of sleep. *British Journal of Psychology, 61,* 473–480.

HOUSTON, B. K. (1968) Inhibition and the facilitating effect of noise on interference tasks. *Perceptual and Motor Skills, 27,* 947–950.

———. (1969) Noise, task difficulty, and Stroop color-word performance. *Journal of Experimental Psychology, 82,* 403–404.

———, and JONES, T. M. (1967) Distraction and Stroop color-word performance. *Journal of Experimental Psychology, 74,* 54–56.

HOWES, D. H., and SOLOMON, R. L. (1951) Visual duration threshold as a function of word-probability. *Journal of Experimental Psychology, 41,* 401–410.

HYMAN, R., and WELL, A. (1968) Perceptual separability and spatial models. *Perception and Psychophysics, 3,* 161–165.

IMAI, S., and GARNER, W. R. (1965) Discriminability and preference for attributes in free and constrained classification. *Journal of Experimental Psychology, 69,* 596–608.

INGLE, D. (1967) Two visual mechanisms underlying the behavior of fish. *Psychologische Forschung, 31,* 44–51.

ITTELSON, W. H. (1952) *The Ames demonstrations in perception: A guide to their construction and use.* Princeton, N.J.: Princeton University Press.

———, and KILPATRICK, R. (1951) Experiments in perception. *Scientific American, 185,* 50–55.

JAMES, W. (1890) *The principles of psychology.* New York: Holt.

JENKS, R. S., and DEANE, G. E. (1963) Human heart rate responses during experimentally induced anxiety: A follow-up. *Journal of Experimental Psychology, 65,* 109–112.

JENSEN, A. R. (1965) Scoring the Stroop test. *Acta Psychologica, 24,* 398–408.

———, and ROHWER, W. D. (1966) The Stroop color-word test: A review. *Acta Psychologica, 25,* 36–93.

JOHNSON, D. A. (1971) Pupillary responses during a short-term memory task: Cognitive processing, arousal, or both? *Journal of Experimental Psychology, 90,* 311–318.

JOHNSON, H. J., and CAMPOS, J. J. (1967) The effect of cognitive tasks and verbalization instructions on heart rate and skin conductance. *Psychophysiology, 4,* 143–150.

JOHNSTON, W. A., GREENBERG, S. N., FISHER, R. P., and MARTIN, D. W. (1970) Divided attention: A vehicle for monitoring memory processes. *Journal of Experimental Psychology, 83,* 164–171.

JONES, L. V. (1954) Distinctiveness of color, form, and position cues for pigeons. *Journal of Comparative and Physiological Psychology, 47,* 253–257.

JONGMAN, R. W. (1968) *Het oog van de meester,* Amsterdam: van Gorcum.

KAFRY, D. (1971) Task complexity and refractoriness in the RSI design. Unpublished M.A. thesis, Hebrew University, Jerusalem. (Hebrew)

KAGAN, J. (1972) Do infants think? *Scientific American, 226,* 74–82.

———, and LEMKIN, J. (1961) Form, color and size in children's conceptual behavior. *Child Development, 32,* 25–28.

———, and LEWIS, M. (1965) Studies of attention in the human infant. *Merrill-Palmer Quarterly, 11,* 95–122.

KAHNEMAN, D. (1968) Method, findings, and theory in studies of visual masking. *Psychological Bulletin, 70,* 404–425.

———. (1970) Remarks on attention control. *Acta Psychologica, 33, Attention and performance III,* ed. A. F. Sanders, 118–131.

———, and BEATTY, J. (1966) Pupil diameter and load on memory. *Science, 154,* 1583–1585.

———, and BEATTY, J. (1967) Pupillary responses in a pitch-discrimination task. *Perception and Psychophysics, 2,* 101–105.

———, BEATTY, J., and POLLACK, I. (1967) Perceptual deficit during a mental task. *Science, 157,* 218–219.

———, BEN-ISHAI, R., and LOTAN, M. (1972) Relation of a test of attention to road accidents. *Journal of Applied Psychology,* in press.

———, and LASS, N. (1971) Eye position in tasks of association and memory. Unpublished manuscript; Hebrew University, Jerusalem.

———, ONUSKA, L., and WOLMAN, R. E. (1968) Effects of grouping on the pupillary response in a short-term memory task. *Quarterly Journal of Experimental Psychology, 20,* 309–311.

———, and PEAVLER, W. S. (1969) Incentive effects and pupillary changes in association learning. *Journal of Experimental Psychology, 79,* 312–318.

———, PEAVLER, W. S., and ONUSKA, L. (1968) Effects of verbalization and incentive on the pupil response to mental activity. *Canadian Journal of Psychology, 22,* 186–196.

———, TURSKY, B., SHAPIRO, D., and CRIDER, A. (1969) Pupillary, heart rate and skin resistance changes during a mental task. *Journal of Experimental Psychology, 79,* 164–167.

———, and WRIGHT, P. (1971) Changes of pupil size and rehearsal strategies in a short-term memory task. *Quarterly Journal of Experimental Psychology, 23,* 187–196.

KALSBEEK, J. W. H., and ETTEMA, J. H. (1963) Continuous recording of heart rate and the measurement of perceptual load. *Ergonomics, 6,* 306–307.

———, and Ettema, J. H. (1964) Physiological and psychological evaluation of distraction stress—Communication at the Second International Ergonomic Conference, Dortmund. *Proceedings of the Second International Congress on Ergonomics,* Supplement to *Ergonomics,* pp. 443–447.

Kaplan, I. T., and Schoenfeld, W. N. (1966) Oculomotor patterns during the solution of visually displayed anagrams. *Journal of Experimental Psychology, 72,* 447–451.

Karlin, L., and Kestenbaum, R. (1968) Effects of number of alternatives on the psychological refractory period. *Quarterly Journal of Experimental Psychology, 20,* 167–178.

Kaufman, L., and Richards, W. (1969) Spontaneous fixation tendencies for visual forms. *Perception and Psychophysics, 5,* 85–88.

Kay, H., and Weiss, A. D. (1961) Relationship between simple and serial reaction time. *Nature, 191,* 790–791.

Keefe, F. B., and Johnson, L. C. (1970) Cardiovascular responses to auditory stimuli. *Psychonomic Science, 19,* 335–337.

Keele, S. W. (1967) Compatibility and time-sharing in serial reaction time. *Journal of Experimental Psychology, 75,* 529–539.

———. (1970) Effects of input and output modes on decision time. *Journal of Experimental Psychology, 85,* 157–164.

———. (1972) Attention demands of memory retrieval. *Journal of Experimental Psychology, 93,* 245–248.

———. (1973) *Attention and human performance.* Pacific Palisades, Calif.: Goodyear.

Keeley, S. M. (1969) Visual detection as a function of attentional demand and perceptual system error. *Perception and Psychophysics, 6,* 73–77.

Kendler, H. H., and Kendler, T. S. (1962) Vertical and horizontal processes in problem solving. *Psychological Review, 69,* 1–16.

———, and Kendler, T. S. (1970a) Developmental processes in discrimination learning. *Human Development, 13,* 65–89.

Kendler, T. S., and Kendler, H. H. (1970b) An ontogeny of optimal shift behavior. *Child Development, 41,* 1–27.

Kendon, A. (1967) Some functions of gaze-direction in social interaction. *Acta Psychologica, 26,* 22–63.

Kinsbourne, M. (1970) The cerebral basis of lateral asymmetries in attention. *Acta Psychologica, 33,* 193–201.

———. (1972) Eye and head turning indicates cerebral lateralization. *Science, 176,* 539–541.

Klein, G. S. (1964) Semantic power measured through the interference of words with color-naming. *American Journal of Psychology, 77,* 576–588.

Kleinsmith, L. J., and Kaplan, S. (1963) Paired-associate learning as a function of arousal and interpolated interval. *Journal of Experimental Psychology, 65,* 190–193.

———, and KAPLAN, S. (1964) Interaction of arousal and recall interval in nonsense syllable paired-associate learning. *Journal of Experimental Psychology, 67,* 124–126.

KLEITMAN, N. (1963) *Sleep and wakefulness.* Chicago: University of Chicago Press.

KOFFKA, K. (1935) *Principles of gestalt psychology.* New York: Harcourt, Brace.

KOHN, B., and BRYDEN, M. P. (1965) The effect of lysergic acid diethylamide (LSD-25) on perception with stabilized images. *Psychopharmacologica, 7,* 311–320.

KORCHIN, S. J. (1964) Anxiety and cognition. In *Cognition: Theory, research, promise,* ed. C. Scheerer. New York: Harper & Row. Pp. 58–78.

KORNBLUM, S., ed. (1972) *Attention and performance IV.* New York: Academic Press, in press.

KRECHEVSKY, I. A. (1932) "Hypotheses" in rats. *Psychological Review, 39,* 516–532.

———. (1938) A study of the continuity of the problem-solving process. *Psychological Review, 45,* 107–133.

KRISTOFFERSON, A. B. (1967) Successive discrimination as a two-state, quantal process. *Science, 158,* 1337–1339.

KROLL, N. E. A., PARKS, T., PARKINSON, S. R., BIEDER, S. L., and JOHNSON, A. L. (1970) Short-term memory while shadowing: Recall or visually and of aurally presented letters. *Journal of Experimental Psychology, 85,* 220–224.

KÜLPE, O. (1904) Versuche über Abstraktion. *Berlin International Congress of Experimental Psychology,* 56–68.

LA BERGE, D., and WINOKUR, S. (1965) Short-term memory using a visual shadowing procedure. *Psychonomic Science, 3,* 239–240.

LACEY, B. C., and LACEY, J. I. (1964) Cardiac deceleration and simple visual reaction time in a fixed foreperiod experiment. Paper presented at the meeting of the Society for Psychophysiological Research, Washington, D.C., October.

———, and LACEY, J. I. (1966) Change in cardiac response and reaction time as a function of motivation. Paper presented at the meeting of the Society for Psychophysiological Research, Denver, October.

LACEY, J. I. (1959) Psychophysiological approaches to the evaluation of the psychotherapeutic process and outcome. In *Research in psychotherapy,* eds. E. A. Rubenstein and M. B. Parloff. Washington, D.C.: American Psychological Association.

———. (1967) Somatic response patterning and stress: Some revisions of activation theory. In *Psychological stress,* eds. M. H. Appley and R. Trumbull. New York: Appleton-Century-Crofts.

———, KAGAN, J., LACEY, B. C., and MOSS, H. A. (1963) The visceral level: Situational determinants and behavioral correlates of autonomic response patterns. In *Expression of the emotions of man.* New York: International Universities Press. Pp. 161–196.

Ladefoged, P., and Broadbent, D. E. (1960) Perception of sequence in auditory events. *Quarterly Journal of Experimental Psychology, 12,* 162–170.

Lappin, J. S. (1967) Attention in the identification of stimuli in complex visual displays. *Journal of Experimental Psychology, 75,* 321–328.

Lashley, K. S. (1942) An examination of the "continuity theory" as applied to discrimination learning. *Journal of General Psychology, 26,* 241–265.

———. (1951) The problem of serial order in behavior. In *Cerebral mechanisms in behavior,* ed. L. A. Jeffries. New York: John Wiley. Pp. 112–136.

———, and Wade, M. (1946) The Pavlovian theory of generalization. *Psychological Review, 53,* 72–87.

Lawrence, D. H. (1949) Acquired distinctiveness of cues: I. Transfer between discrimination of the basis of familiarity with the stimulus. *Journal of Experimental Psychology, 30,* 770–784.

———. (1950) Acquired distinctiveness of cues: II. Selective association in a constant stimulus situation. *Journal of Experimental Psychology, 40,* 175–188.

———. (1963) The nature of a stimulus: Some relationships between learning and perception. In *Psychology: A study of a science,* Vol. 5, ed. S. Koch. New York: McGraw-Hill. Pp. 179–212.

———. (1971) Two studies of visual search for word targets with controlled rates of presentation. *Perception and Psychophysics, 10,* 85–89.

———, and LaBerge, D. L. (1956) Relationship between recognition accuracy and order of reporting stimulus dimensions. *Journal of Experimental Psychology, 51,* 12–18.

Lawson, E. A. (1966) Decisions concerning the rejected channel. *Quarterly Journal of Experimental Psychology, 18,* 260–265.

Levine, M. (1962) Cue neutralization: The effects of random reinforcements upon discrimination learning. *Journal of Experimental Psychology, 63,* 438–443.

Levy, R. (1971) Recognition of dichotic word lists in focused and divided attention. Unpublished M.A. thesis, Hebrew University, Jerusalem. (Hebrew)

Lewis, J. L. (1970) Semantic processing of unattended messages using dichotic listening. *Journal of Experimental Psychology, 85,* 225–228.

Lewis, M., Kagan, J., Campbell, H., and Kalafat, J. (1966) The cardiac response as a correlate of attention in infants. *Child Development, 37,* 63–71.

———, and Spaulding, S. J. (1967) Differential cardiac response to visual and auditory stimulation in the young child. *Psychophysiology, 3,* 229–237.

Libby, W. L., Jr., Lacey, B. C., and Lacey, J. I. (1973) Pupillary and cardiac activity during visual attention. *Psychophysiology,* in press.

LIBERMAN, A. M., COOPER, F. S., SHANKWEILER, D. P., and STUDDERT-KENNEDY, M. (1967) Perception of the speech code. *Psychological Review, 74,* 431–461.

LINDSAY, P. H. (1970) Multichannel processing in perception. In *Attention: Contemporary theory and analysis,* ed. D. I. Mostofsky. New York: Appleton-Century-Crofts. Pp. 149–171.

———, CUDDY, L. L., and TULVING, E. (1965) Absolute judgments of simultaneously presented visual and auditory stimuli. *Psychonomic Science, 2,* 211–212.

———, and NORMAN, D. A. (1969) Short-term retention during a simultaneous detection task. *Perception and Psychophysics, 5,* 201–205.

———, TAYLOR, M. M., and FORBES, S. M. (1968) Attention and multidimensional discrimination. *Perception and Psychophysics, 4,* 113–117.

LOCKHEAD, G. R. (1966a) Effects of dimensional redundancy on visual discrimination. *Journal of Experimental Psychology, 72,* 95–104.

———. (1966b) Visual discrimination and methods of presenting redundant stimuli. *Proceedings of the Seventy-fourth Annual Convention of the American Psychological Association, 1,* 67–68.

LORENS, S. A., JR., and DARROW, C. W. (1962) Eye movements, EEG, GSR and EKG during mental multiplications. *EEG and Clinical Neurophysiology, 14,* 739–746.

LOVEJOY, E. P. (1966) Analysis of the overlearning reversal effect. *Psychological Review, 73,* 87–103.

———. (1968) *Attention in discrimination learning: A point of view and a theory.* San Francisco: Holden-Day.

LOWE, D., and MERIKLE, P. M. (1970) On the disruption of short-term memory by a response prefix. *Canadian Journal of Psychology, 24,* 169–177.

LUBORSKY, L., BLINDER, B., and SCHIMEK, J. (1965) Looking, recalling and GSR as a function of defense. *Journal of Abnormal Psychology, 70,* 270–280.

LURIA, A. R. (1961) *The role of speech in the regulation of normal and abnormal behavior,* ed. J. Tizard. New York: Liveright.

LYNN, R. (1966) *Attention, arousal and the orientation reaction.* Oxford: Pergamon Press.

MACKINTOSH, N. J. (1964) Overtraining and transfer within and between dimensions in the rat. *Quarterly Journal of Experimental Psychology, 16,* 250–256.

———. (1965) Selective attention in animal discrimination learning. *Psychological Bulletin, 64,* 124–150.

———. (1971) An analysis of overshadowing and blocking. *Quarterly Journal of Experimental Psychology, 23,* 118–125.

MACKWORTH, J. F. (1969) *Vigilance and habituation: A neuropsychological approach.* Harmondsworth, Middlesex, England: Penguin Books.

———. (1970) *Vigilance and attention: A signal detection approach.* Harmondsworth, Middlesex, England: Penguin Books.

Mackworth, N. H. (1965) Visual noise causes tunnel vision. *Psychonomic Science, 3,* 67–68.

———, and Bruner, J. S. (1970) How adults and children search and recognize pictures. *Human Development, 13,* 149–177.

———, and Morandi, A. J. (1967) The gaze selects informative details within pictures. *Perception and Psychophysics, 2,* 547–552.

Madsen, M. C., Rollins, H. A., and Senf, G. M. (1970) Variables affecting immediate memory for bisensory stimuli: Eye-ear analogue studies of dichotic listening. *Journal of Experimental Psychology Monograph Supplement, 83,* 1–16.

Malmo, R. B. (1959) Activation: A neuropsychological dimension. *Psychological Review, 66,* 367–386.

———. (1965) Physiological gradients and behavior. *Psychological Bulletin, 64,* 225–234.

———. (1966) Cognitive factors in impairment: A neuropsychological study of divided set. *Journal of Experimental Psychology, 71,* 184–189.

———, and Surwillo, W. W. (1960) Sleep deprivation: Changes in performance and physiological indicants of activation. *Psychological Monographs, 74,* 502.

Maltzman, I., Harris, L., Ingram, E., and Wolff, C. (1971) A primary effect in the orienting reflex to stimulus change. *Journal of Experimental Psychology, 87,* 202–206.

———, and Raskin, D. C. (1965) Effects of individual differences in the orienting reflex on conditioning and complex processes. *Journal of Experimental Research in Personality, 1,* 1–16.

Marcel, A. J. (1970) Some constraints on sequential and parallel processing, and the limits of attention. *Acta Psychologica, 33,* 77–92.

Massaro, D. W. (1972) Preperceptual images, processing time, and perceptual units in auditory perception. *Psychological Review, 79,* 124–145.

McCormack, P. D., and Haltrecht, E. J. (1966) Monitoring eye movements under two conditions of presentation of paired-associate materials. *Canadian Journal of Psychology, 20,* 154–159.

———, Haltrecht, E. J., and Hannah, T. E. (1966) Monitoring eye movements in nonlearning situations. *Psychonomic Science, 6,* 371–372.

———, Haltrecht, E. J., and Hannah, T. E. (1967) Monitoring eye movements during the learning of successive paired-associate lists. *Journal of Verbal Learning and Verbal Behavior, 6,* 950–953.

———, and Hannah, T. E. (1967) Monitoring eye movements during the learning of high and low meaningfulness paired-associate lists. *Psychonomic Science, 8,* 443–444.

———, and Moore, T. E. (1969) Monitoring eye movements during the learning of low-high and high-low meaningfulness paired-associate lists. *Journal of Experimental Psychology, 79,* 18–21.

McDonnell, N. (1967) Effects of intensity, contrast and novelty on selective attention and free-choice reaction-time. Unpublished M.A. thesis, University of Toronto.

McDonnell, P. M. (1970) The role of albedo and contrast in a test of selective attention. *Perception and Psychophysics, 8,* 270–272.

Michon, J. A. (1964) A note on the measurement of perceptual motor load. *Ergonomics, 7,* 461–463.

———. (1966) Tapping regularity as a measure of perceptual motor load. *Ergonomics, 9,* 401–412.

Michotte, A. (1963) *The perception of causality.* London: Methuen.

Miller, G. A., Galanter, E., and Pribram, K. (1960) *Plans and the structure of behavior.* New York: Holt, Rinehart & Winston.

Montague, W. E. (1965) Effect of irrelevant information on a complex auditory-discrimination task. *Journal of Experimental Psychology, 69,* 230–236.

Moray, N. (1959) Attention in dichotic listening: Affective cues and the influence of instructions. *Quarterly Journal of Experimental Psychology, 11,* 56–60.

———. (1967) Where is capacity limited? A survey and a model. *Acta Psychologica, 27,* 84–92.

———. (1969a) *Listening and attention.* Baltimore: Penguin Books.

———. (1969b) *Attention: Selective processes in vision and hearing.* London: Hutchinson Educational Ltd.

———. (1970a) Time sharing in auditory perception: Effect of stimulus duration. *Journal of the Acoustical Society of America, 47,* 660–661.

———. (1970b) Introductory experiments in auditory time sharing: Detection of intensity and frequency increments. *Journal of the Acoustical Society of America, 47,* 1071–1073.

———, and Barnett, T. (1965) Stimulus presentation and methods of scoring in short-term memory experiments. *Acta Psychologica, 24,* 253–263.

———, and Jordan, A. (1966) Practice and compatibility in two-channel short-term memory. *Psychonomic Science, 4,* 427–428.

———, and O'Brien, T. (1967) Signal-detection theory applied to selective listening. *Journal of the Acoustical Society of America, 42,* 765–772.

Morin, R. E., Forrin, B., and Archer, W. (1961) Information-processing behavior: The role of irrelevant stimulus information. *Journal of Experimental Psychology, 61,* 89–96.

Morton, J. (1964) The effects of context upon speed of reading eye movements, and eye-voice span. *Quarterly Journal of Experimental Psychology, 16,* 340–355.

———. (1968) A retest of the response bias explanation of the word-frequency effect. *British Journal of Mathematical and Statistical Psychology, 21,* 21–33.

———. (1969a) Interaction of information in word recognition. *Psychological Review, 76,* 165–178.

———. (1969b) Categories of interference: Verbal mediation and conflict in card sorting. *British Journal of Psychology, 60,* 329–346.

———. (1969c) The use of correlated stimulus information in card sorting. *Perception and Psychophysics, 5,* 374–376.

———. (1970a) A functional model for memory. In *Models of memory,* ed. D. A. Norman. New York: Academic Press. Pp. 203–254.

———. (1970b) The role of memory in the attention process. *Acta Psychologica, 33,* 271–279.

———, CROWDER, R. G., and PRUSSIN, H. A. (1971) Experiments with the stimulus suffix effect. *Journal of Experimental Psychology Monograph, 91,* 169–190.

———, and HOLLOWAY, C. M. (1970) Absence of a cross-model "suffix effect" in short-term memory. *Quarterly Journal of Experimental Psychology, 22,* 167–176.

MOWBRAY, G. H. (1953) Simultaneous vision and audition: The comprehension of prose passages with varying levels of difficulty. *Journal of Experimental Psychology, 46,* 365–372.

———. (1954) The perception of short phrases presented simultaneously for visual and auditory reception. *Quarterly Journal of Experimental Psychology, 6,* 86–92.

———. (1962) Some human perceptual limits. *APL Technical Digest,* Jan.–Feb., 21–24.

———. (1964) Perception and retention of verbal information presented during auditory shadowing. *Journal of the Acoustical Society, 36,* 1459–1465.

MURDOCK, B. B., JR. (1960) The immediate retention of unrelated words. *Journal of Experimental Psychology, 60,* 222–234.

———. (1965) Effects of a subsidiary task on short-term memory. *British Journal of Psychology, 56,* 413–419.

MURRAY, D. J., and HITCHCOCK, C. H. (1969) Attention and storage in dichotic listening. *Journal of Experimental Psychology, 81,* 164–169.

NAYLOR, J. C., BRIGGS, G. E., and REED, W. G. (1968) Task coherence, training time, and retention interval effects on skill retention. *Journal of Applied Psychology, 52,* 386–393.

NEISSER, U. (1963) Decision time without reaction time: Experiments in visual scanning. *American Journal of Psychology, 76,* 376–385.

———. (1967) *Cognitive psychology.* New York: Appleton-Century-Crofts.

———. (1969) Selective reading: A method for the study of visual attention. Presented at the Nineteenth International Congress of Psychology, London.

———, HOENIG, Y. J., and GOLDSTEIN, E. (1969) Perceptual organization in the prefix effect. *Journal of Verbal Learning and Verbal Behavior, 8,* 424–429.

———, NOVICK, R., and LAZAR, R. (1963) Searching for ten targets simultaneously. *Perceptual and Motor Skills, 17,* 955–961.

———, and STOPER, A. (1965) Redirecting the search process. *British Journal of Psychology, 56,* 359–368.

NICKERSON, R. S. (1967) Psychological refractory phase and the functional significance of signals. *Journal of Experimental Psychology, 73,* 303–312.

NINIO, A., and KAHNEMAN, D. (1973) Reaction time in focused and in divided attention. *Journal of Experimental Psychology,* in press.

NORMAN, D. A. (1968) Towards a theory of memory and attention. *Psychological Review, 75,* 522–536.

———. (1969a) *Memory and attention: An introduction to human information processing.* New York: John Wiley.

———. (1969b) Memory while shadowing. *Quarterly Journal of Experimental Psychology, 21,* 85–94.

———, and RUMMELHART, D. E. (1970) A system for perception and memory. In *Models of human memory,* ed. D. A. Norman. New York: Academic Press. Pp. 19–64.

NOTTERMAN, J. M., SCHOENFELD, W. N., and BERSH, P. J. (1952) Conditioned heart rate response in human beings during experimental anxiety. *Journal of Comparative and Physiological Psychology, 45,* 1–8.

NUNNALLY, J. C., FAW, T. T., and BASHFORD, M. B. (1969) The effects of degrees of incongruity on visual fixations of children and adults. *Journal of Experimental Psychology, 81,* 360–364.

———, KNOTT, P. D., DUCHNOWSKI, A., and PARKER, R. (1967) Pupillary response as a general measure of activation. *Perception and Psychophysics, 2,* 149–155.

OBRIST, P. A. (1968) Heart rate and somatic-motor coupling during classical aversive conditioning in humans. *Journal of Experimental Psychology, 77,* 180–193.

———, WEBB, D. M., and SUTTERER, J. R. (1969) Heart rate and somatic changes during aversive conditioning and a simple reaction-time task. *Psychophysiology, 5,* 696–723.

———, WEBB, D. M., SUTTERER, J. R., and HOWARD, J. L. (1970a) The cardiac-somatic relationship: Some reformulations. *Psychophysiology, 6,* 569–587.

———, WEBB, D. M., SUTTERER, J. R., and HOWARD, J. L. (1970b) Cardiac deceleration and reaction time: An evaluation of two hypotheses. *Psychophysiology, 6,* 695–706.

———, WOOD, D. M., and PEREZ-REYES, M. (1965) Heart rate during conditioning in humans: Effects of UCS intensity, vagal blockade, and adrenergic block of vasomotor activity. *Journal of Experimental Psychology, 70,* 32–42.

Olson, R. K., and Attneave, F. (1970) What variables produce similarity grouping? *The American Journal of Psychology, 83,* 1–21.

Oltman, P. K. (1964) Field dependence and arousal. *Perceptual and Motor Skills, 19,* 441.

Osgood, G. E. (1953) *Method and theory in experimental psychology.* New York: Oxford University Press.

Paivio, A., and Simpson, H. M. (1966) The effect of word abstractness and pleasantness on pupil size during an imagery task. *Psychonomic Science, 5,* 55–56.

———, and Simpson, H. M. (1968) Magnitude and latency of the pupillary response during an imagery task as a function of stimulus abstractness and imagery ability. *Psychonomic Science, 12,* 45–46.

Parkinson, S. R. (1972) Short-term memory while shadowing: Multiple-item recall of visually and of aurally presented letters. *Journal of Experimental Psychology, 92,* 256–265.

Pavlov, I. P. (1927) *Conditioned Reflexes,* trans. G. V. Anrep. New York: Dover Publications. (Replication of original, Oxford University Press, ed., 1960.)

Payne, D. T., Parry, M. E., and Harasymin, S. J. (1968) Percentage of pupillary dilation as a measure of item difficulty. *Perception and Psychophysics, 4,* 139–143.

Peavler, W. S. (1969) Attention, processing load, and pupil size. Unpublished Ph. D. thesis, University of Delaware.

Peterson, L. R. (1969) Concurrent verbal activity. *Psychological Review, 76,* 376–386.

Pillsbury, W. B. (1908) *Attention.* New York: Macmillan.

Pollack, I., Rubenstein, H., and Decker, L. (1960) Analysis of incorrect responses to an unknown message set. *Journal of the Acoustical Society of America, 32,* 454–457.

Porges, S. W. (1972) Heart rate variability and deceleration as indexes of reaction time. *Journal of Experimental Psychology, 92,* 103–110.

Posner, M. I. (1964) Information reduction in the analysis of sequential tasks. *Psychological Review, 71,* 491–504.

———. (1969) Abstraction and the process of recognition. In *Advances in learning,* ed. G. Bower. New York: Academic Press.

———. (1970) On the relationship between letter names and super-ordinate categories. *Quarterly Journal of Experimental Psychology, 22,* 279–287.

———, and Boies, S. J. (1971) Components of attention. *Psychological Review, 78,* 391–408.

———, and Keele, S. W. (1968) Attention demands of movements. Paper presented to the Sixteenth International Congress of Applied Psychology, Symposium on Work and Fatigue, August. Published in the Proceedings, Amsterdam, 1969. Swets & Zeitlinger.

———, and KEELE, S. W. (1970) Time and space as measures of mental operations. Invited address, Division 3, American Psychological Association, September.

———, and KLEIN, R. M. (1972) On the functions of consciousness. In *Attention and performance IV,* ed. S. Kornblum. New York: Academic Press, in press.

———, KLEIN, R. M., SUMMERS, J., and BUGGIE, S. (1973) On the selection of signals. *Memory and Cognition, 1,* 2–12.

———, LEWIS, J., and CONRAD, C. (1972) Component processes in reading: A performance analysis. In *Language by ear and by eye,* eds. J. Kavanaugh and I. Mattingly. Boston: MIT Press.

———, and MITCHELL, R. F. (1967) Chronometric analysis of classification. *Psychological Review, 74,* 392–409.

———, and ROSSMAN, E. (1965) Effect of size and location of informational transforms upon short-term retention. *Journal of Experimental Psychology, 70,* 496–505.

———, and WARREN, R. (1972) Traces, concepts and conscious construction. In *Coding theory in learning and memory,* eds. A. W. Melton and E. Martin. New York: Winston, Pp. 25–43.

POULTON, E. C. (1952) The basis of perceptual anticipation in tracking. *British Journal of Psychology, 43,* 295–302.

———. (1953) Two-channel listening. *Journal of Experimental Psychology, 46,* 91–96.

PRATT, R. W. (1970) Cognitive processing of uncertainty: Its effects on pupillary dilation and preference ratings. *Perception and Psychophysics, 8,* 193–198.

PRITCHATT, D. (1968) An investigation into some of the underlying associative verbal processes of the Stroop color effect. *Quarterly Journal of Experimental Psychology, 20,* 351–359.

QUARTON, G. C., and TALLAND, G. A. (1962) The effects of methamphetamine and pentobarbital on two measures of attention. *Psychopharmacologica,* 3, 66–71.

RABBITT, P. M. A. (1964) Ignoring irrelevant information. *British Journal of Psychology, 55,* 403–414.

———. (1967) Learning to ignore irrelevant information. *American Journal of Psychology, 80,* 1–13.

———. (1969) Psychological refractory delay and response-stimulus interval duration in serial, choice-response tasks. *Acta Psychologica, 30, Attention and performance II,* ed. W. G. Koster, 195–219.

———. (1971) Times for the analysis of stimuli and for the selection of responses. *British Medical Bulletin, 27,* 259–265.

RAPAPORT, D. (1967) The theory of attention cathexis: An economic and structural attempt at the explanation of cognitive processes. In *The* *collected papers of David Rapaport,* ed. M. M. Gill. New York: Basic Books. Pp. 778–794.

RASKIN, D. C., KOTSES, H., and BEVER, J. (1969a) Autonomic indicators of orienting and defensive reflexes. *Journal of Experimental Psychology, 80,* 423–433.

———, KOTSES, H., and BEVER, J. (1969b) Cephalic vasomotor and heart rate measures of orienting and defensive reflexes. *Psychophysiology, 6,* 149–159.

RAZRAN, G. (1961) The observable unconscious and the inferable conscious in current Soviet psychophysiology: Introceptive conditioning, semantic conditioning and the orienting reflex. *Psychological Review, 68,* 81–147.

REBER, A. S., and ANDERSON, J. R. (1970) The perception of clicks in linguistic and nonlinguistic messages. *Perception and Psychophysics, 8,* 81–89.

REICHER, G. M. (1969) Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology, 81,* 275–280.

REITMAN, J. S., (1971) Mechanisms of forgetting in short-term memory. *Cognitive Psychology, 2,* 131–157.

REYNOLDS, D. (1964) Effects of double stimulation: Temporary inhibition of response. *Psychological Bulletin, 62,* 333–347.

———. (1966) Time and event uncertainty in unisensory reaction time. *Journal of Experimental Psychology, 71,* 286–293.

REYNOLDS, G. S. (1961) Attention in the pigeon. *Journal of the Experimental Analysis of Behavior, 4,* 203–208.

RIGGS, L. A., RATLIFF, F., CORNSWEET, J. C., and CORNSWEET, T. W. (1953) The disappearance of steadily fixated visual test objects. *Journal of the Optical Society of America, 43,* 495–501.

RUBINSTEIN, L., and RUTSCHMANN, J. (1967) Reduction of the "psychological refractory period." *Perception and Psychophysics, 2,* 499–502.

RUMMELHART, D. E. (1970) A multicomponent theory of the perception of briefly exposed visual displays. *Journal of Mathematical Psychology, 7,* 191–218.

SALAPATEK, P., and KESSEN, W. (1966) Visual scanning of triangles in the human newborn. *Journal of Experimental Child Psychology, 3,* 155–167.

SANDERS, A. F. (1963) The selective process in the functional visual field. Monograph from Institute for Perception, National Defense Research Organization TNO. Soesterberg, The Netherlands.

———. (1970) Some aspects of the selective process in the functional visual field. *Ergonomics, 13,* 101–117.

———, and KEUSS, P. J. G. (1969) Grouping and refractoriness in multiple selective responses. *Acta Psychologica, 30,* 177–194.

———, and SCHROOTS, J. J. F. (1968) Cognitive categories and memory span: I. Shifting between categories. *Quarterly Journal of Experimental Psychology, 20,* 370–372.

SAVIN, H. B. (1967) On the successive perception of simultaneous stimuli. *Perception and Psychophysics, 2,* 479–482.

SCHAEFER, T., JR., FERGUSON, J. B., KLEIN, J. A. and RAWSON, E. B. (1968) Pupillary responses during mental activities. *Psychonomic Science, 12,* 137–138.

SCHLOSBERG, H. (1954) Three dimensions of emotion. *Psychological Review, 61,* 81–88.

SCHNEIDER, G. E. (1967) Contrasting visuomotor functions of tectum and cortex in the golden hamster. *Psychologische Forschung, 31,* 52–62.

SCHOUTEN, J. F., KALSBEEK, J. W. H., and LEOPOLD, F. F. (1962) On the evaluation of perceptual and mental load. *Ergonomics, 5,* 251–260.

SCHVANEVELDT, R. W. (1969) Effects of complexity in simultaneous reaction time tasks. *Journal of Experimental Psychology, 81,* 289–296.

SCHWARTZ, F., and SCHILLER, P. H. (1967) Rapaport's theory of attention cathexis. *Bulletin of the Menninger Clinic, 31,* 3–17.

———, and SCHILLER, P. H. (1970) A psychoanalytic model of attention and learning. *Psychological Issues, 6* (3), Monograph 23. New York: International Universities Press.

SEIBEL, R. (1963) Discrimination reaction time for a 1,023-alternative task. *Journal of Experimental Psychology, 66,* 215–226.

SENDERS, J. W. (1965) An investigation of the visual sampling behavior of human observers. Bolt, Beranek, and Newman, Report No. 1246.

SHAFFER, L. H. (1968) Refractoriness in information processing. *Quarterly Journal of Experimental Psychology, 20,* 38–50.

———. (1971) Attention in transcription skill. *Quarterly Journal of Experimental Psychology, 23,* 107–112.

———, and HARDWICK, J. (1969a) Reading and typing. *Quarterly Journal of Experimental Psychology, 21,* 381–383.

———, and HARDWICK, J. (1969b) Monitoring simultaneous auditory messages. *Perception and Psychophysics, 6,* 401–404.

———, and HARDWICK, J. (1970) The basis of transcription skill. *Journal of Experimental Psychology, 84,* 424–440.

SHEPARD, R. N. (1964) Attention and the metric structure of the stimulus space. *Journal of Mathematical Psychology, 1,* 54–87.

SHEPP, B. E., KEMLER, D. G., and ANDERSON, D. R. (1972) Selective attention and the breadth of learning: An extension of the one-look model. *Psychological Review, 79,* 317–328.

SHIFFRIN, R. M., and GARDNER, G. T. (1972) Visual processing capacity and attentional control. *Journal of Experimental Psychology, 93,* 72–82.

SHULMAN, H. G., and GREENBERG, S. N. (1971) Perceptual deficit due to division of attention between memory and perception. *Journal of Experimental Psychology, 88,* 171–176.

———, GREENBURG, S. N., and MARTIN, J. (1971) Intertask delay as a parameter of perceptual deficit in divided attention. *Journal of Experimental Psychology, 88,* 439–440.

Simon, H. A., and Barenfeld, M. (1969) Information-processing analysis of perceptual processes in problem solving. *Psychological Review, 76,* 473–483.

Simon, J. R. (1969) Reactions toward the source of stimulation. *Journal of Experimental Psychology, 81,* 174–176.

———, Craft, J. L., and Small, A. M., Jr. (1970) Manipulating the strength of a stereotype: Interference effects in an auditory information-processing task. *Journal of Experimental Psychology, 86,* 63–68.

Simpson, H. M., and Hale, S. M. (1969) Pupillary changes during a decision-making task. *Perceptual and Motor Skills, 29,* 495–498.

———, Molloy, F. M., Hale, S. M., and Climan, M. H. (1968) Latency and magnitude of the pupillary response during an imagery task. *Psychonomic Science, 13,* 293–294.

———, and Paivio, A. (1966) Changes in pupil size during an imagery task without motor response involvement. *Psychonomic Science, 5,* 405–406.

———, and Paivio, A. (1968) Effects on pupil size of manual and verbal indicators of cognitive task fulfillment. *Perception and Psychophysics, 3,* 185–196.

Smith, E. E. (1968) Choice reaction time: An analysis of the major theoretical positions. *Psychological Bulletin, 69,* 77–110.

———, and Haviland, S. E. (1972) Why words are perceived more accurately than nonwords: Inference versus unitization. *Journal of Experimental Psychology, 92,* 59–64.

Smith, F. (1969) The use of featural dependencies across letters in the visual identification of words. *Journal of Verbal Learning and Verbal Behavior,* 8, 215–218.

Smith, M. C. (1967a) The psychological refractory period as a function of performance of a first response. *Quarterly Journal of Experimental Psychology, 19,* 350–352.

———. (1967b) Theories of the psychological refractory period. *Psychological Bulletin, 67,* 202–213.

———. (1967c) Reaction time to a second stimulus as a function of intensity of the first stimulus. *Quarterly Journal of Experimental Psychology, 19,* 125–132.

———. (1969) The effect of varying information on the psychological refractory period. *Acta Psychologica, 30, Attention and performance II,* ed. W. G. Koster, 220–231.

Snyder, C. R. R. (1972) Selection, inspection, and naming in visual search. *Journal of Experimental Psychology, 92,* 428–431.

Sokolov, E. N. (1963) *Perception and the conditioned reflex,* trans. S. W. Waydenfold. Oxford: Pergamon Press.

———. (1965) The orienting reflex, its structure and mechanisms. In *Orienting reflex and exploratory behavior*, eds. L. G. Voronin, A. N. Leontiev, A. R. Luria, E. N. Sokolov, and O. S. Vinogradova. Russian Monographs on Brain and Behavior, 3. American Institute of Biological Sciences, Washington, D. C.

———. (1969) The modeling properties of the nervous system. In *A handbook of contemporary Soviet psychology*, eds. M. Cole and I. Maltzman. New York: Basic Books.

SPERLING, G. (1960) The information available in brief visual presentations. *Psychological Monographs, 74*, (Whole No. 498).

———. (1963) A model for visual memory tasks. *Human Factors, 5*, 19–31.

———. (1967) Successive approximations to a model for short-term memory. *Acta Psychologica, 27*, 285–292.

———, BUDIANSKY, J., SPIVAK, J. G., and JOHNSON, M. C. (1971) Extremely rapid visual search: The maximum rate of scanning letters for the presence of a numeral. *Science, 174*, 307–311.

SPIETH, W., CURTIS, J. F., and WEBSTER, J. C. (1954) Responding to one of two simultaneous messages. *Journal of the Acoustical Society of America, 26*, 390–396.

SPOEHR, K. T., and SMITH, E. E. (1972) The role of syllables in perceptual processing. In press.

STENNETT, R. G. (1957) The relationship of performance level to level of arousal. *Journal of Experimental Psychology, 54*, 54–61.

STERNBERG, S., and KNOLL, R. L. (1972) The perception of temporal order: Fundamental issues and a general model. In *Attention and performance IV*, ed. S. Kornblum. New York: Academic Press. In press.

———, KNOLL, R. L., and GATES, B. A. (1971) Prior entry reexamined: Effect of attentional bias on order perception. Paper presented at the meeting of the Psychonomic Society, November, St. Louis, Mo.

STRONGMAN, K. (1970) Communicating with the eyes. *Science Journal, 6*, 47–52.

STROOP, J. R. (1935) Studies of interference in serial verbal reactions. *Journal of Experimental Psychology, 18*, 643–662.

SUCHMAN, R. G., and TRABASSO, T. (1966a) Color and form preference in young children. *Journal of Experimental Child Psychology, 3*, 177–187.

———, and TRABASSO, T. (1966b) Stimulus preference and cue function in young children's concept attainment. *Journal of Experimental Child Psychology, 3*, 188–198.

SUTHERLAND, N. S. (1959) Stimulus analyzing mechanisms. In *Proceedings of a symposium on the mechanization of thought processes, II*. London: Her Majesty's Stationery Office. Pp. 575–609.

———. (1964) The learning of discrimination by animals. *Endeavour, 23*, 148–152.

———, and Holgate, V. (1966) Two-cue discrimination learning in rats. *Journal of Comparative and Physiological Psychology, 4,* 198–207.

———, and Mackintosh, J. (1964) Discrimination learning: Non-additivity of cues. *Nature, 201,* 528–530.

———, Mackintosh, N. J., and Mackintosh, J. (1965) Shape and size discrimination in octopus: The effects of pretraining along different dimensions. *Journal of Genetic Psychology, 106,* 1–10.

———, and Mackintosh, N. J. (1971) *Mechanisms of animal discrimination learning.* New York: Academic Press.

Tanner, W. P., Jr., and Swets, J. A. (1954) A decision-making theory of visual detection. *Psychological Review, 61,* 401–409.

Taylor, M. M., Lindsay, P. M., and Forbes, S. M. (1967) Quantification of shared capacity processing in auditory and visual discrimination. *Acta Psychologica, 27,* 223–229.

Tecce, J. J. (1972) Contingent negative variation (CNV) and psychological processes in man. *Psychological Bulletin, 77,* 73–108.

Telford, C. W. (1931) The refractory phase of voluntary and associative responses. *Journal of Experimental Psychology, 14,* 1–35.

Thackray, R. I. (1969) Patterns of physiological activity accompanying performance in a perceptual motor task. FAA Office of Aviation Medicine Report. No. 69–8.

Thomas, E. L. (1963) Eye movements and fixations during initial viewing of Rorschach cards. *Journal of Projective Techniques and Personality Assessment, 27,* 345–353.

———, and Lansdown, E. L. (1963) Visual search patterns of radiologists in training. *Radiology, 81,* 288–292.

Tikhomirov, O. K., and Poznyanskaya, E. D. (1966) An investigation of visual search as a means of analyzing heuristics. *Soviet Psychology, 5* (2), 3–15. (Trans. from *Voprosy Psikhologii, 12,* 39–53.)

Tinker, M. A. (1947) Time relations for eye-movement measures in reality. *Journal of Educational Psychology, 38,* 1–10.

———. (1958) Recent studies of eye movements in reading. *Psychological Bulletin, 55,* 215–231.

Titchener, E. B. (1908) *Lectures on the elementary psychology of feeling and attention.* New York: Macmillan.

Trabasso, T. R. (1963) Stimulus emphasis and all-or-none learning in concept identification. *Journal of Experimental Psychology, 65,* 398–406.

———, and Bower, G. H. (1968) *Attention in learning: Theory and research.* New York: John Wiley.

Treisman, A. M. (1960) Contextual cues in selective listening. *Quarterly Journal of Experimental Psychology, 12,* 242–248.

———. (1964a) Verbal cues, language and meaning in selective attention. *American Journal of Psychology, 77,* 206–219.

———. (1964b) Effect of irrelevant material on the efficiency of selective listening. *American Journal of Psychology, 77,* 533–546.

———. (1964c) Monitoring and storage of irrelevant messages in selective attention. *Journal of Verbal Learning and Verbal Behavior, 3,* 449–459.

———. (1964d) Selective attention in man. *British Medical Bulletin, 20,* 12–16.

———. (1969) Strategies and models of selective attention. *Psychological Review, 76,* 282–299.

———. (1970) Perception and recall of simultaneous speech stimuli. *Acta Psychologica, 33,* 132–148.

———. (1971) Shifting attention between the ears. *Quarterly Journal of Experimental Psychology, 23,* 157–167.

———, and DAVIES, A. (1972) Divided attention to ear and eye. In press.

———, and FEARNLEY, J. S. (1969) The Stroop test: Selective attention to colors and words. *Nature, 222,* 437–439.

———, and FEARNLEY, J. S. (1971) Can simultaneous speech stimuli be classified in parallel? *Perception and Psychophysics, 10,* 1–7.

———, and GEFFEN, G. (1967) Selective attention and cerebral dominance in perceiving and responding to speech messages. *Quarterly Journal of Experimental Psychology, 19,* 1–17.

———, and GEFFEN, G. (1968) Selective attention and cerebral dominance in perceiving and responding to speech messages. *Quarterly Journal of Experimental Psychology, 20,* 139–151.

———, and RILEY, J. G. A. (1969) Is selective attention selective perception or selective response? A further test. *Journal of Experimental Psychology, 79,* 27–34.

TREISMAN, M. (1971) On the word frequency effect: Comments on the papers by J. Catlin and L. H. Nakatani. *Psychological Review, 73,* 420–425.

———. (1972) Detection of binaural tone stimuli: time sharing or criterion change? *Journal of the Acoustical Society of America, 51,* 625–630.

TREVARTHEN, C. B. (1968) Two mechanisms of vision in primates. *Psychologische Forschung, 31,* 299–337.

TRIGGS, T. J. (1968) Capacity sharing and speeded reactions to successive signals. Technical Report No. 9, August, University of Michigan, Contract No. AF 49(638)-1736, United States Department of Defense.

TRUMBO, D., and NOBLE, M. (1970) Secondary task effects on serial verbal learning. *Journal of Experimental Psychology, 85,* 418–424.

———, NOBLE, M., and SWINK, J. (1967) Secondary task interference in the performance of tracking tasks. *Journal of Experimental Psychology, 73,* 232–240.

TULVING, E., and GOLD, C. (1963) Stimulus information and contextual information as determinants of tachistoscopic recognition of words. *Journal of Experimental Psychology, 66,* 319–327.

———, and LINDSAY, P. H. (1967) Identification of simultaneously presented simple visual and auditory stimuli. *Acta Psychologica, 27,* 101–109.

TURSKY, B., SCHWARTZ, G. E., and CRIDER, A. (1970) Differential patterns of heart rate and skin resistance during a digit-transformation task. *Journal of Experimental Psychology, 83,* 451–457.

ULEMAN, J. S., and REEVES, J. (1971) A reversal of the Stroop interference effect through scanning. *Perception and Psychophysics, 9* (3A), 293–295.

UNDERWOOD, B. J., RUNQUIST, W. N., and SCHULZ, R. W. (1959) Response learning in paired-associate lists as a function of intralist similarity. *Journal of Experimental Psychology, 58,* 70–78.

———, and SCHULZ, R. W. (1960) *Meaningfulness and verbal learning.* Philadelphia: Lippincott.

UNDERWOOD, G., and MORAY, N. (1972) Shadowing and monitoring for selective attention. *Quarterly Journal of Experimental Psychology, 23,* 284–296.

UNGER, S. M. (1964) Habituation of the vasoconstrictive orienting reaction. *Journal of Experimental Psychology, 67,* 11–18.

UNO, T., and GRINGS, W. W. (1965) Autonomic components of orienting behavior. *Psychophysiology, 1,* 311–321.

VINCE, M. (1948) The intermittency of control movements and the psychological refractory period. *British Journal of Psychology, 38,* 149–157.

VON WRIGHT, J. M. (1968) Selection in visual immediate memory. *Quarterly Journal of Experimental Psychology, 20,* 62–68.

———. (1970) On selection in visual immediate memory. *Acta Psychologica, 33,* 280–292.

WACHTEL, P. L. (1967) Conceptions of broad and narrow attention. *Psychological Bulletin, 68,* 417–429.

WALKER, E. L., and TARTE, R. D. (1963) Memory storage as a function of time with homogeneous and heterogeneous lists. *Journal of Verbal Learning and Verbal Behavior, 2,* 113–119.

WALTER, W. G., COOPER, R., ALDRIDGE, V. J., MCCALLUM, W. C., and WINTER, A. L. (1964) Contingent negative variation: An electric signal sensorimotor association and expectancy in the human brain. *Nature, 203,* 380–384.

WEBB, R. A., and OBRIST, P. A. (1970) The physiological concomitants of reaction time performance as a function of preparatory interval series. *Psychophysiology, 6,* 389–403.

WEBSTER, J. C., and SOLOMON, L. N. (1955) Effects of response complexity upon listening to competing messages. *Journal of the Acoustical Society of America, 27,* 1194–1198.

———, and THOMPSON, P. O. (1954) Responding to both of two overlapping messages. *Journal of the Acoustical Society of America, 26,* 396–402.

WEG E. (1971) Unpublished study, Hebrew University, Jerusalem. (Hebrew)

WEITZMAN, B. (1963) A threshold difference produced by a figure-ground dichotomy. *Journal of Experimental Psychology, 66,* 201–205.

WELFORD, A. T. (1952) The "psychological refractory period" and the timing of high-speed performance: A review and a theory. *British Journal of Psychology, 43,* 2–19.

———. (1959) Evidence of a single-channel decision mechanism limiting performance in a serial reaction task. *Quarterly Journal of Experimental Psychology, 11,* 193–210.

———. (1967) Single-channel operation in the brain. *Acta Psychologica, 27,* 5–22.

———. (1968) *Fundamentals of skill.* London: Methuen.

WELL, A. (1971) The influence of irrelevant information on speeded classification tasks. *Perception and Psychophysics, 10,* 79–84.

WHEELER, D. D. (1970) Processes in word recognition. *Cognitive Psychology, 1,* 59–85.

WILCOCKS, R. W. (1925) An examination of Külpe's experiments on abstraction. *American Journal of Psychology, 36,* 324–341.

WILKINSON, R. T. (1961) Interaction of lack of sleep with knowledge of results, repeated testing and individual differences. *Journal of Experimental Psychology, 62,* 263–271.

———. (1962) Muscle tension during mental work under sleep deprivation. *Journal of Experimental Psychology, 64,* 565–571.

———. (1963) Interaction of noise with knowledge of results and sleep deprivation. *Journal of Experimental Psychology, 66,* 332–337.

———. (1965) Sleep deprivation. In *The physiology of human survival,* eds. O. G. Edholm and A. L. Bacharach. London and New York: Academic Press. Pp. 399–430.

WILLIAMS, L. G. (1966) The effect of target specification on objects fixated during visual search. *Perception and Psychophysics, 1,* 315–318.

WILSON, R. S. (1964) Autonomic changes produced by noxious and innocuous stimulation. *Journal of Comparative and Physiological Psychology, 58,* 290–295.

WOLFORD, G., and BOWER, G. H. (1969) Continuity theory revisited: Rejected for the wrong reasons? *Psychological Review, 76,* 515–518.

WOODWORTH, R. S. (1938) *Experimental psychology.* New York: Holt.

———. (1958) *Dynamics of behavior.* New York: Holt.

WRIGHT, P., and KAHNEMAN, D. (1971) Evidence for alternative strategies of sentence retention. *Quarterly Journal of Experimental Psychology, 23,* 197–213.

YARBUS, A. L. (1967) *Eye movements and vision,* trans. B. Haigh. New York: Plenum Press.

YERKES, R. M., and DODSON, J. D. (1908) The relation of strength of stimulus to rapidity of habit-formation. *Journal of Comparative Neurology of Psychology, 18,* 459–482.

YNTEMA, D. C., and TRASK, F. P. (1963) Recall as a search process. *Journal of Verbal Learning and Verbal Behavior, 2,* 65–74.

ZEAMAN, D. and HOUSE, B. J. (1963) The role of attention in retardate discrimination learning. In *Handbook of mental deficiency: Psychological theory and research.* New York: McGraw-Hill. Pp. 159–223.

ZELNIKER, T. (1971) Perceptual attenuation of an irrelevant auditory verbal input as measured by an involuntary verbal response in a selective-attention task. *Journal of Experimental Psychology, 87,* 52–56.

ZIMNY, G. H., and KIENSTRA, R. A. (1967) Orienting and defensive responses to electric shock. *Psychophysiology, 3,* 351–362.

———, and MILLER, F. L. (1966) Orienting and adaptive cardiovascular responses to heat and cold. *Psychophysiology, 3,* 81–92.

———, PAWLICK, G. F., and SAUR, D. P. (1969) Effects of stimulus order and novelty on orienting responses. *Psychophysiology, 6,* 166–173.

Name Index

Subject Index