Chapter 20

ATTENTION

Richard M. Shiffrin, Indiana University

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Concepts, theories, and research concerning attention have come to play a major role in almost every subfield within psychology. Contributing to this prominence is the generality of the construct. Attention has been used to refer to all those aspects of human cognition that the subject can control (like those aspects that Atkinson and Shiffrin, 1968, termed control processes), and to all aspects of cognition having to do with limited resources or capacity, and methods of dealing with such constraints.

The pervasiveness of attention in cognition was accepted from the earliest days of psychology, and the term was used almost synonymously with cognition and consciousness (e.g. James, 1890; Pillsbury, 1908). Although attentional research has continued throughout the intervening years, the central status of the concept was lost with the rise of behaviorism (circa 1920), probably because most prior research had been based on introspective methods. The modern upsurge in attentional research and theory began about 1950 among applied psychologists and engineers concerned with man-machine interactions and communication and information theory. The field grew rapidly following publication of Broadbent's book in 1958.

The coverage in this chapter will be quite limited, focusing upon a few of the important themes that have motivated the greatest theoretical interest and empirical study: These include automatism and control, dividing and focusing of resources during perception, locus and generality of capacity limitations, and stimulus and task characteristics important for the understanding of these issues. The reader interested in more comprehensive coverage within the cognitive, perceptual, and performance areas is referred to the continuing series of edited volumes titled Attention and Performance (12 volumes thus far), a volume entitled Varieties of Attention edited by Parasuraman and Davies (1984), and books by Broadbent (1958, 1971), Kahneman (1973), Keele (1973), Moore (1969a,b), Posner (1978), Underwood (1976), Norman (1968), and Neisser (1967, 1976). These sources refer to most of the important studies, though they themselves represent only a small sample of the extant literature.

Everyone who has worked in the field of attention has made note of the organism's limited ability to process information and carry out actions. These are usually termed capacity limitations or resource limitations. At times there
appears to be a pure trading relationship in force, such that extra resources devoted to one task or process need to be borrowed (at a cost) from some other task or process. Furthermore, attention is often conceived as a relatively slow and serial activity, the focus of attention being in one place at one time. It had been equally clear to workers in the field that normal human behavior could not take place if all activity had to be governed by attentive processes operating in such a limited fashion. Almost any skilled activity, whether involving actions (e.g., sports, music performance, typing, automobile driving) or mental operations (e.g., reading, retrieving information from memory, perceiving) is carried out with such a complex set of operations operating in concert (in parallel) that much of the behavior must be occurring outside the normal focus of attention. Parity for this reason, all researchers have incorporated various types of automatic processes into their theories. Much of the research and theory testing in the field has been directed toward understanding the roles of automatic and attentive processes. A common theoretical view of perceptual processing places automatic processes (often termed preattention) at an early stage, followed by limited attentive processes. An alternative theoretical view, to be explored in this chapter, assumes automatic and attentive processes operate interactively and concurrently, at most stages of processing.

Regardless of one’s theoretical perspective, it is clear that automatic processes and attention go hand in hand, an understanding of one requiring an understanding of the other. We shall therefore begin this chapter by assessing the characteristics of automatic and attentive processes. Such distinctions date back to the beginning of psychology, and it is useful to start by reviewing some research carried out around the turn of the century.

EARLY STUDIES CONCERNING AUTOMATIZATION

Skill Development

Skill acquisition is one of the most fundamental topics in psychology. One of the best known and earliest studies of the relationship of skill acquisition to attention and automation1 was carried out by Bryan and Harter (1886). They studied the development of ability to send and receive telegraph messages (short and long pulses arranged in coded groups). Figure 11.1 shows representative learning curves for two subjects. Sending exhibits a relatively smooth improvement to an asymptote. Receiving exhibits two phases: a growth to a first asymptote, and then, for connected discourse, another rise to a second asymptote.

Subjective reports by expert telegraph receivers suggested a gradual shift in focus of attention during learning, from letters to words, to phrases or groups, and then to meaning. At the same time the attention demands drop, so that the expert can take the message and yet think about the sense of the message or even about other matters entirely. Expert testimony and evidence suggested it may take ten years of practice to reach the point where the receiver finds the task to become relatively free of effort, so asymptotic automatization is no easy matter to achieve in this fairly complex task.

Bryan and Harter (1886) concluded that the receiver learns by acquiring a hierarchy of habits, from letters to syllables, to words, to phrases, to higher language habits. These are acquired simultaneously, but not equally. Movements to higher stages of expertise must await sufficient automatization of the elements lower in the hierarchy of habits. The length of any plateau in development is a measure of the difficulty of making the lower-order habits sufficiently automatic. The rapid rise afterward represents a “quick realization of powers potentially present by reason of preceding gradual and unconscious habituation.” (Sending presumably shows no plateau because finger movements limit performance starting at an early stage of learning.)

Bryan and Harter suggested that the rate of processes in consciousness does not increase with practice so much as the amount included in each process, consistent with their hierarchical view. They concluded that “There is no freedom except through automatism.” That is, automatism

1The noun representing a state of automatic processing has traditionally been “automation” (stress on the second syllable). In recent years, the term “automativity” (stress on the first syllable) has become quite prevalent. The traditional usage will be followed in this chapter.

Figure 11.1. Telegraph learning performance for two subjects tested by Bryan and Harter (1886). Top panel shows learning to send and receive messages. Bottom panel shows receiving data only, for three types of material. From “Studies on the Telegraphic Language: The Acquisition of a Hierarchy of Habits” by W.L. Bryan and N. Harter, 1886. Psychological Review, 6, p. 350.

frees attention for other uses. This hypothesis, and indeed most of the suggestions of Bryan and Harter (and other early psychologists) are still an important part of present-day distinctions between automatic and attentive processes.

It should be noted that the plateaus observed by Bryan and Harter (and shown in Figure 11.1) are observable only rarely, possibly because successive stages of skill acquisition tend to merge smoothly into one another. Keller (1959) reviewed other studies of telegraphy (receiving) and noted that learning proceeded smoothly and regularly, without plateaus (and indeed took place far more quickly than indicated in Figure 11.1). On the basis of these observations Keller suggested additional and different mechanisms involved in telegraphy (phonological recoding and other similar processes). Although the alternative proposals are also compatible with Bryan and Harter’s views concerning automatization, they do suggest that the telegraph receiver could receive automatically, without utilizing resources, or both. Thus, more stringent tests of automatization are needed. In one such test the subject would carry out a second attention-demanding task concurrently with the telegraphy task. As telegraphy becomes increasingly automatized, it should become possible to carry out both tasks together with increasing efficiency. Dual task
studies of this sort (though not involving telegraphy) are discussed next.

**Dual Task Studies**

Solomons and Stein (1936) set out to demonstrate that fairly complex tasks could be automatized. They used a dual task technique because they wished awareness to be removed from one task, and the presence of another task seemed a plausible way to accomplish this goal. In one task, one of the authors silently read an interesting story while writing down an occasional word dictated by the other (the reader scribbling continuously between dictations). Introspections revealed several stages of learning: (1) Generalized difficulty with both tasks; (2) Rapid attention switching from the story to dictation and back when necessary; (3) Less and less effort needed for dictation; (4) Dictation occurred without volition, though awareness of writing something remained; (5) Writing occurred entirely without awareness (this occurred only occasionally). With enough practice, the loudness of the dictated word could drop close to the threshold of easy hearing without affecting the automation. Finally, the authors noted that memory for the written words disappeared rather early in training.

In another study Solomons and Stein found it easy to learn to read in a low voice something uninteresting while listening with full attention to an interesting story read aloud at normal loudness. Quite a different situation occurred when the two subjects each read aloud something different at equal loudness, each trying to attend to the other. In this situation each was aware of hearing both voices, although grasping the meaning of only one (normally the one to be attended).

Although these introspections were useful, Downey and Anderson (1915) were motivated to obtain objective data in a similar paradigm. In the second of their five studies, the subjects (Downey and Anderson) continuously wrote perfectly memorized verse, while silently reading chapters of a novel. (The same verse was written over and over throughout the study.) Figure 11.2 gives the control ("normal") reading and writing times when only one task is carried out, and the corresponding times when both tasks are carried out together. Anderson came close to being able to carry out both tasks together at rates comparable to those holding for single tasks, possibly because he reported a tendency to read visually, a whole paragraph at a time (reading aloud caused greater deficits). Attempts to introspect tended to interfere with dual task performance and incidental suggestions were not reported. Retrospections revealed for both subjects an increasing tendency to lose awareness of the writing, especially when an exciting chapter was read (although writing was not greatly affected).

Downey and Anderson's fifth task was similar to that used by Solomons and Stein: Reading was done aloud and dictation consisted of continuous writing of dictated stories. The task seemed relatively easy to the subjects but a dual task deficit in performance was observed even after considerable practice. Both subjects remembered the reading material well; Anderson remembered as well much of what was dictated, although Downey had little consciousness of writing and recalled very little of the dictation. Downey and Anderson concluded that in most of their tasks, true simultaneity of operations, without cost, could not be achieved. At least one of the tasks usually showed some deficit (although dual task performance was nonetheless impressive). They suggested the deficit could be explained not by a failure to develop some type of automatism, but by an increased effort needed to keep two processes going together, or by a specific interference with either of the operations (these ideas are reflected in recent proposals, e.g., Neven and Gopher, 1979). Finally, Downey and Anderson interpreted their lapses of awareness of dictation as lapses of memory rather than failures of perception (ideas reflected in recent proposals, e.g., Deutsch and Deutsch, 1965; Stofflin, 1975a).

A few modern dual task studies related to these are worthy of mention in this section. Allport, Antonia, and Reynolds (1972) used students who were skilled enough to play the piano by sight-reading. These students took part in two sessions of training in which they attempted to sight-read piano pieces of differing difficulty and also shadow (repeat word for word) auditory prose passages of differing difficulty. By session two, both sight-reading and shadowing could be carried out together as well as either alone. Furthermore, memory for the prose material was as good in the dual task conditions as in the single task control conditions. The authors argued that the results could not be explained by rapid and continuous attention shifts between the two tasks, and hence argued against a single, central attention bottleneck. They suggested the existence of a number of independent, specific and broad processes were operating in parallel. Bottlenecks of attention are in this view due to tasks requiring use of the same processors. The authors did not give much consideration to automatization as a basis for, or as an alternative to, the development of special processors. If either or both tasks had become automatized (probably sight reading, since this skill had been practiced pre-experimentally), then the notion of a central attention bottleneck could have been retained.

Shaffer (1975) tested a skilled typist in various conditions. She could: (1) Type visually presented material and simultaneously recite nursery rhymes fluently, with a cost of only about 10 percent in typing speed and errors; (2) Type and simultaneously shadow (repeat aloud) prose dictated at 140 words per minute, with only a 10 percent cost; (3) Type and simultaneously shadow random letters dictated once per second, with only a 10 percent cost (but shadowing exhibited a 20 percent performance drop). In other conditions the typing was done from auditory dictation. While typing dictation from a male voice in one ear, shadowing dictation from a female voice in the other ear proved difficult—typing speed and accuracy were poor, and shadowing was very error prone. Similarly poor results were obtained when the typing was done from auditory dictation, and the shadowing from visual input. Shaffer concluded that "attention is a control process which directs translation processing to an orderly (intended) completion." Presumably attention is needed more in the unpracticed typing from dictation tasks. Shaffer argued that all stimuli impacting on the senses are brought into contact automatically with a richly connected semantic memory, but that attention is needed to prevent the information from being dissected in nonsystematic processing. The possibility of explaining the dual task results on the basis of automatism of certain types of typing was not considered because Shaffer felt that automatization "begs the question of what is attention."

Hinz, Spilke, Reaves, Cacharel, and Neisser (1980) had subjects read stories (easy) or encyclopedias (hard), while writing down dictated material simultaneously. The dictation
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The core area of selective attention research in the modern era is concerned with the detection or location of signals. Stimuli are presented and the subject tries to detect or locate the presence of target stimuli at least some of whose characteristics are defined in advance. The findings of greatest interest from an attentional viewpoint are the increases in performance that occur when the number of sources of stimuli increases, when stimulus uncertainty increases, when the number of stimuli increases, or when the number of targets increases. In the following we shall focus upon paradigms in which the stimuli are presented visually, termed visual search. Some greater power is available in the visual modality than, say, the auditory modality because of the relative ease with which many stimuli may be presented simultaneously.

Terminology

The set of stimuli that the subject is instructed to detect on a trial is called the memory set. Sometimes there is a larger group of stimuli from which the memory set is chosen in successive trials. If so, this set is called the memory ensemble. The set of stimuli presented on a trial is called the display set (whether presented simultaneously or successively). The display set includes targets, distractors, or both. The distractor set is the group of stimuli presented on a trial that are not in the memory set. When the distractor sets on successive trials are chosen from a larger group of stimuli, the larger group is called the distractor ensemble. The stimuli from the memory set that are presented in (the display set) on a trial are called targets.

When the display set contains just one item, and memory set size varies, then the paradigm is called memory search. When the display set size varies, the paradigm is called visual search. When the display set is presented successively (regardless of the number of stimuli in a single frame, or the overlap between frames), the paradigm is termed a multiple frame task.

Threshold detection tasks involve displays presented briefly so that significant numbers of errors would be made even were the memory set size and display set size both equal to one. Thus, in threshold tasks errors and performance levels will be a mixture of attention effects and sensory failures. Since our interest is primarily in attention, rather than in structural limitations of
the peripheral sensory system, we will focus discussion upon above-threshold tasks. These are usually divided into two classes: (1) Those in which the set sizes are small enough that errors are of very few, called reaction time tasks; (2) Those in which the set sizes are large enough and the search time available small enough that many errors are made, called accuracy tasks.

The potential difficulty of a given task is often indexed by the load, defined as the product of memory set size and display set size. However, when the display consists of a series of separated, successive frames, the load is instead defined as the product of memory set size and frame size: frame size is the number of stimuli presented in a given frame. Which meaning of load is meant will always be clear in context, since all the multiple-frame tasks we will discuss will utilize nonoverlapping frames of constant size.

Two basic paradigms will be considered. Consistent mapping (CM) refers to tasks in which the memory ensemble and the distracter ensemble do not overlap, hence, targets from one trial are never distractors on another, and vice versa. Varied mapping (VM) refers to tasks in which consistent mapping is not maintained. In most such tasks, targets on one trial are distractors on others, and vice versa.

In many studies, targets appear only on some trials (usually 50 percent). The subject attempts to identify the presence or absence of targets as quickly or accurately as possible. Target-present trials are termed positive, and target-absent trials negative.

**Memory Search**

The prototype for memory search studies was carried out by Sternberg (1966). Digits were used as stimuli, and targets were present on 50 percent of the trials. Memory set size varied from one to six, across trials. The results from the varied mapping study are shown in Figure 11.3. Reaction time is slightly slower for negative responses, and rises as a linear function of load (memory set size), with about equal slopes for negative and positive functions.

**Serial-Exhaustive Comparisons**

Sternberg (1966) proposed a serial-exhaustive comparison model to account for the results. The visual display item is compared to each memory set item in turn (hence the term serial).

![Figure 11.3. Relation between response latency and the number of symbols in memory, s, from Sternberg (1966). Mean latencies, over eight subjects, of positive responses (filled circles) and negative responses (open circles). About 65 observations per point. For each s, overall mean and standard error are indicated. Solid line was fitted by least squares to overall means. Upper bound for parallel process (broken curve).](image)

The successive comparison times have identical distributions. The comparisons continue until the memory set is exhausted (hence the term exhaustive), regardless of whether a match is encountered before all comparisons are complete.

Response time in this model consists of a base term representing all processes not involved in comparisons (such as perception, encoding, deciding, and motor-responding), plus the sum of times for the various comparisons. The base time has its own distribution, but is independent of the memory set size. The base time has a slightly larger mean for the negatives, possibly shown in the linear function of load (memory set size), with about equal slopes for negative and positive functions.

**Potential Problems**

The basic memory search findings (i.e., linear, parallel set-size functions) have been replicated in endless variations. However, certain data seem to raise problems for the serial-exhaustive comparison model. The first set of problems concern the existence of errors and the possibility that the shape of the set-size functions could be affected by a trade-off of accuracy for speed. In fact, accuracy is virtually always increased with set size (see Sternberg, 1975, also see Figure 11.3). If a trade-off were operating, then an inducement for the subjects to equate errors at all set sizes would produce steeper slopes than those observed. When error rates rise above about 10 percent, it is difficult to discuss slopes because the basic linearity of the set-size functions is usually lost (e.g., Reed, 1976). However at rates below 10 percent the slopes and shapes of the functions change very little, even when subjects are instructed to increase speed at the cost of accuracy (see Sternberg, 1975). Thus for typical memory search studies worries about the form of the data caused by differential error rates are probably unfounded.

A second class of findings from varied-mapping memory search studies have also produced problems for the serial-exhaustive model. An item that is a target much more often than others, that is peculiarly salient, that is especially marked, that appears more than once in a given memory set, or that the subject decides to occur as a test item, will produce an especially fast response when tested (for a summary see Shiffrin & Schneider, 1973, or Sternberg, 1975). The set size functions are shifted downward for such items, but the slope remains largely unchanged. Possibly related to such findings are the observations of serial position effects: Reaction time is dependent upon the presentation position of the test item within the memory set, especially when the time interval between study and test is short (see Sternberg, 1975, for a review).

These findings are not easy to reconcile with an exhaustive serial search, if the source of the effects is in the comparison process. In a test-terminating search, the order of the search determines reaction time for positive responses. In an exhaustive search, order is irrelevant since all memory set items are compared. Also arguing against the source of the effect being in the comparison process is the fact that distractions that are salient also show intercept changes rather than slope changes (Shiffrin & Schneider, 1973). Therefore, the serial exhaustive model can be salvaged only if such effects take place in stages before the process other than the comparison stage: the encoding, decision, or motor-response stages (a not unreasonable assumption: see Miller and Pachella, 1973).

**Alternative Models**

Although the effects just discussed may be consistent with the serial-exhaustive model, they have encouraged the development of alternative models. Most of these involve some form of parallel, concurrent comparisons. We must distinguish between two kinds of models. In one, all memory set items are compared to the test item simultaneously, with distributions of completion times that do not depend upon the size of the memory set. When this is true, the time to complete the slowest of the comparisons rises with memory set size. Nevertheless, it can be shown that such models cannot predict the observed data (see Sternberg, 1966, and the dashed line in Figure 11.3). On the other hand, if one allows comparison time to depend on memory set size (i.e., a limited capacity approach), then it can be shown that there are always exist parallel models that will match the predictions of a given serial model (e.g., Townsend, 1976). For present purposes, it is important to note that all the alternative models proposed for memory search data have been based upon limited capacity in some form: when the comparisons are to be concurrent, the rate at which each is completed is assumed to be given as memory set-size goes up.
Training Effects in Varied Mapping Tasks

Given the dramatic effects of extended training that were reviewed in the first section, it is important to examine the effects of practice upon memory search. Kristofferson (1972a) trained subjects for 30 days in a varied mapping memory search study similar to that used by Sternberg (1966). The results are shown in Figure 11.4. The slope remained constant (at 36 msec per comparison) during the entire course of training, but the intercept decreased from 350 to 200 msec. The intercept, of course, reflects components of the search task that are not changed over trials, components that are practiced in consistent fashion (such as, say, the motor response). The fact that the slope does not change suggests a rather fixed attentional or capacity limitation that cannot be removed by practice (a conclusion to be contrasted with that drawn by Hirst et al., 1980).

Attentional Implications

There are important attentional features in the varied-mapping memory search results. First, there is a strict capacity limit; each comparison takes about 40 additional msec; thus memory search is an example of time sharing of attentional processes. Second, there is great effort associated with the task, according to subjective reports. Third, the task occupies attention to the extent that it is difficult, if not impossible, to carry out any other attention demanding task simultaneously (we will present the evidence shortly). Fourth, the attentional limitations in varied-mapping settings do not change with practice. (But note that "awareness" of the comparison process seems to be lacking in detail, possibly because it occurs so quickly, and evidence that the subject can control the process, say, by switching from an exhaustive to a terminating searching mode, is not available.)

Training Effects in Consistent Mapping Tasks

When consistent mapping is used during memory search, practice produces marked slope reductions. In consistent mapping the memory ensemble and the distractor ensemble remained fixed over trials. No memory set item is ever a distractor and vice versa. The memory set on a given trial consists of a choice of items from the memory ensemble, so it is still possible to vary memory set size. Kristofferson (1972b) trained subjects in memory search using consistent mapping for 86 days. The results are shown in Figure 11.5. The set-size functions are nonlinear from the first few sessions onward. The nonlinearity makes slope analysis problematic, but however one defines it, the slope does drop consistently with training. These changes certainly imply that the serial exhaustive comparison model is inappropriate. It would not be sensible to argue, for example, that the subject increasingly ignores the presented memory set (since the memory set is well learned), thereby flattening the slope. Such an argument would imply that practice leads the subject to operate less efficiently, since attention to the memory set would improve performance. Furthermore, as we shall see in the section on visual search, consistent practice leads to reduced reaction times at large set sizes (comparatively varied conditions), rather than increased reaction times at small set sizes. It is more likely that some sort of automatic detection process has developed, a process that is increasingly insensitive to load. We will return to this hypothesis, and other alternatives, after considering results from visual search tasks.

Visual Search

In this section are considered search studies in which (most of) the trials have a display set greater than one.

Stimulus Factors

Perhaps the single most prominent factor in visual search is related to the similarity and confusability of the items. By now, hundreds of studies testify to the positive relationship between speed of search and the similarity difference between targets and distractors, and this relationship transcends considerations of type of training and other factors. (One example of the large performance differences that can arise due to physical differences among targets is seen in Table 11.1 from a study to be described shortly). And Treisman and her colleagues have argued in a number of recent papers that many of these effects are due to the need to use limited attentional resources to integrate features that are processed automatically and separately by the perceptual system (e.g., Treisman & Gelade, 1980). John Duncan, Glynn Humphreys, and colleagues have suggested that feature conjunction effects are subsumed under more general considerations of stimulus similarity, with search being speeded by dissimilarity of targets to distractors, and by similarity of distractors to each other (e.g., Quinlan & Humphreys, in press; Duncan, 1986 in press). Whatever the basis for similarity effects, they are powerful enough in some cases to take precedence over effects of training.
Table 11.1. Comparison of the estimated probability \( p \) of correctly detecting the location of (i) a known numeral and (ii) an unknown one-of-ten numerals. Nine-letter arrays were presented at ISI's of 60 msec, approximately 180 trials were used to estimate each \( p \).

<table>
<thead>
<tr>
<th>Numerals</th>
<th>Known</th>
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<td>.011</td>
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<td>1</td>
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<td>2</td>
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<td>.642</td>
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<td>.906</td>
</tr>
<tr>
<td>8</td>
<td>.719</td>
<td>.648</td>
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<td>.477</td>
<td>.633</td>
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<tr>
<td>Mean</td>
<td>.464</td>
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</tbody>
</table>

extremely high. For example, in my laboratory Mary Chorwinski has examined visual search with memory set size of one. When the target is a four letter word and distractors are four letter words sharing a random three letters with the target, even 24 sessions of training failed to produce differences between consistent and varied conditions (and search rates were high: about 100 msec per word). Such results point to limits on the ability of consistent training to produce automatic detection in visual search.

The second situation occurs when target-distractor confusability is extremely low, and stimuli are not very complex. In many such situations search shows no effect of load regardless of the consistency of training, and indeed the load independent processing is seen at the onset of the experiment, before training has taken place. Simple examples would include detecting a target of one color among distractors of a clearly different color, or detecting an X among O's or an O among X's. To take just one case, Donderi (1963, Experiment 1) demonstrated no effect of display size in a varied mapping study in which subjects were to say whether a display contained all identical letters, or one discrepant letter (see also Treisman & Souther, 1985, for some examples). In such situations it is clear that a feature(s) capable of leading directly to a correct response is extracted automatically from the display, even without training.

Despite the existence of visual search cases in which training has little effect, there are many cases where training effects are large, and these cases can provide important evidence concerning differences between automatic and attentive processes. Studies of this type are considered next.

**Varied-Mapping Studies**

In varied-mapping paradigms, search time is usually a linear function of load (in situations where eye movements are not a contaminating source of performance variation). Atkinson, Holmgren and Juola (1969) utilized memory set size of one and varied display size. They obtained linear functions that were parallel for negative and positive responses. Reaction time was not affected by display position of a target. However, more often than not in visual search studies, the slopes of the negative responses are twice that for positive responses. One example of such data, from Hockley (1984), is shown in Figure 11.6. Also shown are the effects of visual display position for each frame size. The strong display position effects may have been induced by the procedure. The memory set item was presented at the center of fixation. The test stimuli were then presented two seconds later, in a vertical array, with the topmost item in the same position as the previous memory set item.

As noted earlier, set size functions that are linear, with negative slopes twice positive slopes, are consistent with a serial, terminating, comparison process. It is not clear what experimental conditions produce two-to-one slope ratios, but a rule of thumb seems to be the following: The more complex the search task, the greater the load, and the slower the average response time, the more likely are two-to-one slope ratios.

Increases in complexity can be achieved by varying both memory-set size and display set size. Examples of such paradigms are provided by Schneider and Shiffrin (1977) and Briggs and Johnson (1973). The results were quite similar, and those from Schneider and Shiffrin (1977, Experiment 2) are presented in Figure 11.7. The memory set size and frame size both ranged from one to four (all conditions blocked). The predicted functions are generated from a type of serial, terminating model: A memory set item is chosen and compared with each displayed item in turn, with a mean time of 42 msec per comparison; then a new memory set item is chosen, and the comparisons continue, the mean time needed to choose each new memory set item is


Figure 11.7. Mean reaction times from the varied-mapping search conditions of Experiment 2 from Schneider and Shiffrin (1977, F = frame size). Predictions derived from the theory described in the text. From "Control and Automatic Human Information Processing: I. Detection, Search, and Attention" by W. Schneider and R. Shiffrin, 1977, Psychological Review, 84, p. 24. Copyright 1977 by the American Psychological Association. Reprinted by permission of the publisher and author.
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Figure 11.6. Variance of the reaction times from the varied-mapping conditions from Experiment 2 from Shiffrin and Schneider (1977). (F = frame size). Predictions from the model described in the text. From "Controlled and Automatic Human Information Processing: I. Detection, Search, and Attention" by W. Schneider and R. Shiffrin, 1977, Psychological Review, 84, p. 25. Copyright 1977 by the American Psychological Association. Reprinted by permission of the publisher and author.

40 msec. This model superior to other serial terminating models that were considered. The same model fit the Briggs and Johnson data quite well, but with a mean comparison time of 57 msec and a mean switching time of 27 msec.

The results we have presented thus far have been concerned with mean reaction times. However, examination of other characteristics of the reaction time distributions proves quite informative. The variance estimates are particularly revealing when the means show linearity with two-to-one slope ratios. When comparisons are independent, variance according to serial models should be a linear, increasing function of the number of comparisons made. For negative responses, the number of comparisons equals the load; variance is indeed observed to be a linear increasing function (see Figure 11.7). On the other hand, when positive responses are determined by a terminating process there are two components making up the variance: (1) a component growing linearly with load, at half the rate of the negative function; (2) a component representing the random stopping point of the comparison process. As the load rises, the second of these components becomes increasingly important. Thus the variances of positive responses are predicted to rise in a curvilinear fashion, the positive variance being less than the negative variance when the load is small but crossing over and becoming greater than the negative variance when the load is high (even though the mean positive reaction time remains at one-half of the mean negative reaction time at all loads).

Results showing this pattern, from Schneider and Shiffrin (1977), for the same data giving rise to the results in Figure 11.7, are shown in Figure 11.8. The predicted functions are from the same model used to generate the predictions shown in Figure 11.7.

The shapes of the reaction time distributions may also be informative. Distributions for correct negative responses, for each set size, for one of the subjects in Hockley's study (1984) are depicted in Figure 11.8. In the case of memory search the modes of the distributions remain fixed, but the skewness increases. In the case of visual search, the distributions tend to shift upward by constant amounts. Each of these patterns is consistent with serial comparison processes; however, the distribution of a comparison would have to differ considerably in the two cases, with a much larger variance and skewness in the case of memory search. It is not known whether the difference in the distribution patterns for visual and memory search shown in Figure 11.9 generalizes to other studies. Nevertheless it should be kept in mind that comparison operations might be different in memory search (with one display item) and visual search (with one memory set item). Other evidence suggesting differences between memory search and visual search may be found in Flach (1986).

In summary, there are some important differences between memory search and visual search involving slope ratios of positive to negative responses and the nature of the respective comparison processes. Nevertheless, the use of varied mapping often shows that reaction time is a linear function of load, and the results are consistent with a serial comparison process. Such results indicate a limited attentional capacity.

Consistent Mapping Studies
In visual search with consistent mapping, early results were obtained by Neisser (1963) who showed that the rate of search become much faster with practice. Furthermore, in one study search for 10 items in the memory set could be carried out as rapidly as for one (Neisser, Novick, & Lazar, 1963). The technique used by Neisser involved many lines of characters pre sented on a printed sheet. The subject scans down the sheet until locating the target. This problem with this technique (and with related techniques using card-sorting) is that eye movements (and/or hand movements) are needed to bring successive groups of items into focal vision. Eye movements are relatively slow (4 or 5 pe seconds) and could be establishing a mechanical limit on search speed. Kristofferson (1972) used a similar technique, but with varied mapping and argued that eye movements were not hindering the search rate. If she was correct in the assertion, it may be that serial search continue during eye movements so that no comparison time is lost. The same is not true when consistent mapping is used, as demonstrated by Sperling.
ATTENTION

Figure 11.10. Mean reaction times for correct responses, and percentages of error, as a function of memory set size, for all conditions, for both varied and consistent search conditions from Experiment 2 of Schneider and Shiffrin (1977). From "Controlled and Automatic Human Information Processing: I. Detection, Search, and Attention" by W. Schneider and R. Shiffrin, 1977, Psychological Review, 84, p. 19. Copyright 1977 by the American Psychological Association. Reprinted by permission of the publisher and author.

Budiansky, Spivak, and Johnson (1977). They used a method in which accuracy was the dependent measure: Displays of items were presented in rapid succession on each trial, each display in foveal vision so that eye movements were not needed. In this study much faster rates were attained that would be possible were eye movements used. Thus, we will focus our discussion upon studies not dependent on eye movements.

Studies by Schneider and Shiffrin (1977) and Briggs and Johnson (1973) used a reaction time measure, consistent mapping, and varied both memory set size and frame size from one to four. We will present the Schneider and Shiffrin (1977) data because their subjects trained much longer. The data from well practiced subjects are shown in Figure 11.10, along with data from the varied mapping conditions on the same subjects at comparable levels of practice (repeated from Figure 11.7). The notable characteristic of these data is the relative flatness of the set size function. The load has very little effect, whether defined by memory set size or display size. The contrast with the varied mapping results is particularly striking. It should be pointed out that these functions are not completely flat. Most consistent mapping studies produce substantially larger effects of load than are seen here (sometimes nonlinear), though still much smaller than the load effects seen in varied mapping conditions.

In summary, when targets and distractors are not too easily discriminable, varied-mapping search studies produce linear search functions with substantial slopes, consistent with serial comparison processes (exhaustive or terminating in different studies). Extended practice lowers reaction times, but the rate of search remains constant. When targets and distractors are not too confusable, consistent mapping leads to a flattening of the reaction time function of load, which most researchers have interpreted as a switch from serial to parallel search, or from limited parallel to partially unlimited parallel search.

It is tempting to suggest, as did Shiffrin and Schneider (1977), that search becomes increasingly automatized in consistent paradigms. (Tests of this hypothesis involve variants of the paradigm that will be discussed in the next section.) Increasing automatization could, of course, produce increasingly flat set size functions. At first glance, such a prediction appears consistent with the data. However, in many cases the degree of flattening seems to cease at some point in training (e.g. the data from Kristofferson, 1972b; Figure 11.5). One could assume that automatic detection is only partially unlimited, even after asymptotic training in consistent paradigms (e.g. Fisher, 1982, 1984). Alternatively, performance may remain limited or of (almost) unlimited automatic detection and a concurrent serial search. This would be possible because automatic processes might be able to occur concurrently with attentive processes. Both processes could operate in parallel with the first to finish triggering the response. If the automatic process is independent of load, then the serial process will tend to finish much more often when the load is small, producing faster responses only at small set sizes. According to this account curvilinear set size functions could be seen even after considerable consistent practice has produced (almost) complete automatization. Data suggesting such an analysis were collected by Ellis and Chase (1971), whose distractors differed from targets in size or color, and by Jones and Anderson (1982), whose distractors differed from targets in category membership. Evidence that performance in visual search is governed jointly by a parallel detection system and a system that depends on a gradually moving focus of attention is reported by Jodides (1968a,b; 1980) and Eriksen and Yeh (1985).

**Figure 11.11.** Two examples of a positive trial in the multiple frame search paradigm of Experiment 1 from Schneider and Shiffrin (1977). (A) varied mapping with memory set = (J, D); and (B) consistent mapping with memory set = (4, 7, 8, 5). (1) presentation of memory set; (2) fixation dot present on for 3 sec when subject starts trial; (3) the memory frames that never contain target; (4) target frame; (5) distractor frames; (6) dummy frames that never contain target. Frame time is varied across conditions. From "Controlled and Automatic Human Information Processing: I. Detection, Search, and Attention" by W. Schneider and R. Shiffrin, 1977, Psychological Review, 84, p. 11. Copyright 1977 by the American Psychological Association. Reprinted by permission of the publisher and author.

**Search Paradigms**

**VARIED MAPPINGS**

**MEMORY SET SIZE = 2**

**FRAME SIZE = 4**

**CONSISTENT MAPPINGS**

**MEMORY SET SIZE = 2**

**FRAME SIZE = 4**

**Visual Search with Accuracy Measures**

Accuracy and reaction time measures of search performance ought to be related in lawful ways. Sperling et al. (1971) used a consistent mapping task with a digit target contained in a long sequence of letter displays. The time per display was varied between trials and the subject attempted to identify the location of the target within the display. A certain degree of automatization seemed to develop, since subjects were able to search for any one of ten digits about as rigidly as for an average, single, known digit. The relevant performance levels are given in Table 11.1. Note that there is enormous variation in detection accuracy over the set of targets (presumably based on the visual similarity of the target to the distractors), but the size of the memory set makes very little difference. Such a result mimics those we have presented in the reaction-time domain.

Schneider and Shiffrin (1977) used a technique based on that of Sperling et al. (1971). They used both varied and consistent mapping. The subjects were those that produced the reaction time data shown in Figure 11.7. A trial consisted of 20 consecutive four-item frames arranged as a square, each presented for 1 sec. Display positions not used for characters were filled with random dot masks. A target occurred in a random position on a random frame (except the first three and last two), on half the trials; the other trials contained no target. An example of a varied and consistent trial is depicted in Figure 11.11. (For this subject the varied items were all letters; these letters were also the consistent distractors; the consistent targets were digits.)

For every condition, the time per display was varied across trials, so as to produce psychometric functions. The accuracy results as a function of frame time, for each load condition and each type of mapping, are shown in Figure 11.12.

In varied mapping the task was enormously difficult, especially at high loads. When the load was 15, even 800 msec per display only allowed 76 percent accuracy of detection. In the varied condition almost all errors were omissions, or misses; there were few false alarms. This would be expected if a serial comparison process were operating, one that would switch to the next items as each new frame was presented. Schneider and Shiffrin (1977) were able to predict rather roughly the performance in these conditions by utilizing the comparison time distributions that fit the reaction time data (Figure 11.17) and assuming a serial comparison process.

The consistent mapping data are quite different. The task can be carried out at much faster display rates. Accuracy is relatively little affected by load, and false alarms occur about as often as misses. This latter result suggests that the source of variability is not in the limited attentional system, instead the errors may arise in the peripheral sensory system. Presumably the characters are presented so briefly they cannot be identified clearly even at the lowest load (of one per display). Norman and Bobrow (1975)
have called this a "data limitation," as opposed to a "process limitation," since the data provided to the processing system is impoverished and no attentional allocation can improve matters (a related distinction is that between state and process limitation; Garner, 1974). Note that even at the smallest load, the varied conditions are inferior to the consistent conditions. This is to be expected, since the successive frames must be dealt with serially in the varied conditions, but may be dealt with in parallel in the consistent conditions. In summary, then, the multiple frame search paradigm, using accuracy as a dependent measure, produces results that are comparable to those in single frame tasks using reaction time as a measure.

Despite the enormous differences between the consistent and varied conditions illustrated in Figure 11.12, a careful look reveals differences as a function of load within the consistent conditions. This point was made even more clearly in studies carried out by Fisher (1984). Analysis of data from his study using consistent mapping and a multiple frame technique suggested that subjects performed about equally well when twice as many items were presented at one half the presentation rate. Fisher proposed a model (1982, 1984) in which consistent training leads to only partially unlimited processing. He suggested that a maximum of about four simultaneous, unlimited comparisons from a visual display could be carried out together. Alternatively, one could argue that load effects in consistent mapping are due to concurrent use of attentional serial search along with automatic, unlimited detection. (In the previous section, this argument was used to explain load effects in consistent mapping when reaction time was the dependent measure.) Further research will be needed to discriminate these competing explanations.

Whether consistent training produces unlimited or partially unlimited automatic detection, the training effects that are observed may be related to the training effects obtained by the earliest psychologists. It seems natural to suggest that the serial search seen in varied mapping paradigms is identified with an attention-demanding control process, and that the gradual improvement seen in consistent mapping may track the development of automatic processes that carry out detection in parallel.

The Effects of Task Reversal

It is conceivable that consistent training simply causes the discriminability of targets and distractors to increase. If so, one might expect that after training the roles of targets and distractors could be reversed without loss of performance. Reversal of roles is not merely a matter of saying "yes" where formerly one said "no" and vice versa. Instead, the roles are reversed so that in memory search (some 0 of the former distractors are presented as memory set items, and in visual search all but at most one of the displayed items are the former targets. Regardless, the superior discrimination mechanisms that have presumably been learned should operate in this new task.

Shiffrin and Schneider (1977) carried out several tests of this kind, with similar results. In one task, subjects were consistently trained to detect consonants from one half of the alphabet in distractors consisting of consonants from the other half of the alphabet. They used a multiple frame paradigm similar to that depicted in Figure 11.11, with accuracy as the dependent measure. Memory set size was four, and each of the 20 displays contained two letters and was presented for 200 msec.

The results of the initial training are shown as the triangles in Figure 11.13. Performance improved rapidly, seen primarily as an increase in the hit rate (detection of targets). After 1500 trials, the display duration was reduced to 120 msec for the next 600 trials. Performance seemed fairly stable at this point, so a reversal was now undertaken. Display time was returned to 200 msec and the targets and distractors exchanged roles. (The subjects were told this would occur; they predicted they would perform well after reversal.)

The reversal results are shown in Figure 11.13 as circles. Performance not only did not remain stable, but dropped well below the level seen at the start of original training. Almost 900 trials were needed to return to that initial performance level and gradual relearning occurred thereafter. A clearer result could hardly be imagined: certainly the hypothesis of increased...
Discriminability of memory set items and distractors may be ruled out as an explanation for the consistent training effects. (For completeness, it should be noted that similar reversal results are obtainable using reaction time tasks; Dumas, 1957; Shiffrin, Dumas, & Schneider, 1961; Schneider, Dumas, & Shiffrin, 1984.) What the reversal results do suggest is an automation of attention itself.

**Automation of Attention**

Shiffrin and Schneider (1977) suggested that the tendency for particular stimuli to attract attention is altered by consistent training: targets come to attract attention more than distractors as training proceeds, independently of the subject's own attempt to allocate attention through active control on a trial by trial basis. The hypothesis holds that stimuli have a normal automatic tendency to attract attention when presented. If more than one item occurs at a time, then the items will compete against each other for attention. If no item is much better at attracting attention than another, then attention will either drift randomly to some item or, more likely, go to an item selected by the subject using momentary attentional control. Presumably this situation holds at the start of training, and throughout varied search mapping practice. On the other hand, when one stimulus attracts attention preferentially, then this item will tend to be checked first in any comparison process. This process presumably operates in consistent tasks after training is well along, and explains the independence of performance from visual display size.

The reversal findings of the preceding section are explicable according to this hypothesis: After reversal, attention is attracted to the former targets which are now distractors; since distractors are checked first, performance is worse than in the varied mapping case or the case holding at the start of practice in which attention is given to items in effectively random order.

However, additional mechanisms are needed to explain the independence of performance from memory set size. For example, when there is only one display item, it will be attended regardless of type of training. Thus automatic attention attraction must be augmented by additional automatic processes before an adequate model is reached. It is possible that the fact that a test item calls strongly for attention is in and of itself sufficient to identify it as a target, regardless of the number of memory set items. Alternatively, a target response separate from the attention response could be learned.

**Automatic Categorization**

Both of these suggestions may well be correct, but there is little if any data that bear on their validity. On the other hand, a categorization hypothesis can explain the lessening of the memory-set-size slope, and much evidence supports this view. The categorization hypothesis has two parts: (1) all the targets in consistent training are learned as a category; (2) when a target item appears for test, the category "label" is extracted automatically (in the same fashion that the item's "name" is extracted). When this hypothesis holds, then a test item need only have its category checked, effectively making the memory set size one. A number of results in the literature are consistent with this view (see Shiffrin and Schneider, 1977, for a review).

Shiffrin and Schneider (1977) experimentally separated the process of category automatization from the development of an automatic attention response. They used a special type of varied training: the stimuli consisted of eight characters divided into two sets of four so that there was maximum visual confusion between the two sets (e.g., GMPF, CNHD). The memory set items were chosen from one of these sets and the distractors from the other, but the roles were random from trial to trial. Thus, although the mapping was varied, the four-item sets stayed together throughout training, allowing each to be learned as a "category." Memory set size was varied (two or four) and a multiple frame technique was used with two items per frame. If the four items became learned as categories, and if a target item was extracted automatically for each test item, then each test item need only have its category checked in order to come to a correct decision. In effect, the memory set size would become "one." This condition was contrasted with a normal varied search procedure using eight other characters, with random selections on every trial so no categorical structure could be learned.

The results are shown in Figure 11.14. At first performance is better for the smaller memory set sizes in both conditions. However, as would be expected if categories are learned, the "category" conditions improve with training until they are equal, and superior to the control conditions (which still differ with memory set size). It appears as if the memory set size in the categorial condition is effectively one. However, automatic detection was not yet operating. At that point, all conditions were switched to completely consistent training (one of the learned categories forming the target ensemble in the experimental condition, and four randomly chosen items forming the target ensemble in the control condition). Performance rose considerably and rapidly, and all conditions became equal, indicating automatic detection had been learned.

The results of this study and the reversal study suggest some sources of automatization. At least two factors operate: (1) targets come to attract attention automatically (and distractors repel it); (2) automatic categorization develops for the memory ensemble (and possibly for the distractor ensemble). These two factors can explain the independence of performance from memory set size and display size in consistently mapped search.

Are these in fact the mechanisms that produce the consistent mapping results? It is possible that the same mechanisms that produce automatic categorization will simultaneously produce automatic responses of other sorts, such as a response of "target." That is, when the displayed item is presented it may lead automatically to an internal response such as "category 1," another internal response such as "target," and other relevant responses that have been consistently trained. Thus although the memory-set-size independence could be due to automatic categorization, it could be due as well to an automatic "target" response. These factors could be operating together and further research would be necessary to isolate them.

Although automatic categorization may underlie automatic detection in memory search, it is an open question whether it underlies automatic detection in visual search when memory set size is one. If an item's category is encoded automatically, an automatic attention response to that encoding could be learned. However, in most cases either a feature of an item, the item's identity, or the item's category could serve as a basis for response. All of these could be encoded...
The Relationship of Automation to Attention

The hypothesis that an automatic attention response is learned provides quite a contrast with the automation that was studied by investigators such as Solomons and Stein (1980), Downey, and Anderson (1986), Shafiri and Shifer (1976), Allport et al. (1972), Spelke et al. (1976), and Hirst et al. (1980). In those dual task studies, especially the earliest ones, the object was to produce an automatic process that would operate without attention. To a certain degree, these investigators succeeded. Stimuli were presented, processed, and responded to with little conscious awareness, and little interference with a concurrent task was observed. A key difference between the dual task and the search studies may be the presence of an attention demanding primary task in the dual task paradigm; perhaps under these circumstances the subject learns to direct attention away from the secondary task that is being automated. This redirection is apparently possible without significantly harming the performance of the secondary task. It would be interesting to learn whether automatic detection in search tasks could be learned without concomitant attention attraction, but the data are not available.

There is little question that an automatic attention response is learned in consistent search tasks. Although the reversal results shown in Figure 11.13 suggest such a conclusion, a study by Shifer and Shifer (1977) addressed this point directly. They first consistently trained a set of characters until automatic detection was well established. (Slopes of search functions were near zero). Then a new task was used in which subjects searched a series of rapidly presented four-item frames for memory set items. Although each frame contained four items arranged in a square, only the items on one diagonal, the same for all frames, were relevant for the task. The memory set items and distractors on this relevant diagonal were all items that had been used in varied mapping search previously, and the search in the present task also used varied mapping. On one third of the trials, one target was present on the relevant diagonal of one of the 20 frames that made up a trial.

Almost all the stimuli that appeared on the irrelevant diagonal were chosen from the same set pool that was used for the relevant diagonal. However, on two thirds of the trials, one stimulus that appeared on the irrelevant diagonal of one of the frames had previously been given consistent training as a target. If the stimulus had developed the ability to attract attention automatically, then it should have continued to do so in the study described. To see whether this was the case, Shifer and Shifer (1977) examined performance on the relevant, varied diagonal as a function of the number of displays between the relevant target and the irrelevant, presumably automatic, target, on trials when both were present. In particular, when the two targets were in the same display, attention attraction to the irrelevant automatic target should cause attention removal from the relevant target. The results are given in Figure 11.16. The dashed line represents detection probability when the "automatic" item is not present. Notice that there is a 22 percent drop in the probability of relevant target detection when an automatic item in a known-to-be-relevant location occurs in the same display. This occurred even though the subjects knew that such automatic items would occur only in irrelevant locations, and were told to ignore them completely.

When no automatic items are presented, then performance on the relevant diagonal is identical to that when only two items are presented per frame. Thus in the absence of automatic items, attention can be focused entirely upon the relevant diagonal. The fact that subjects could not maintain their attention focus in the presence of "automatic" irrelevant items suggests that the consistent training of items as target causes a training of the attention system itself. When an automatic target appears, it attracts attention, albeit briefly, causing a relevant target somewhere else to be missed. This attention attraction occurs despite all attempts by the subject to force attention to relevant locations and items. (This result is related to a number of findings in search tasks showing that two simultaneous targets can interfere with each other; e.g., see Shifer and Shifer, 1977, Experiments 3 a,b,c and Duncan, 1980.)

The time course of attention attraction and its rebound can be estimated, very roughly, from the results in Figure 11.15. The displays in a trial occurred every 200 msec. A slight drop in performance occurs even when the automatic item is on the display subsequent to the target. Thus the attention attraction must occur quite rapidly. Possibly controlled serial search from one display overlaps the physical presentation of the next display. If so, a rapid withdrawal of attention caused by an item in that second display could cause some performance loss due to premature interruption of the controlled search of the preceding display. On the other hand, attention rebounds quickly—when the target is in the display following the automatic item, a negligible performance drop takes place. It seems plausible to interpret these findings in terms of the temporary shift away from the relevant diagonal, and back again, within a total of 200 msec (and probably less). As we shall see, there are longer switching time estimates from other studies, but the described study has an unusual feature—the subject is attempting to fix attention on the relevant diagonal, and the temporary shift is automatically driven. Were this not the case, shifts of attention could be slower.

Although these results suggest that targets attract attention automatically, it ( attempted important question: Does consistent training cause distractions to repulse attention? A study by Dumas (1978) found that Shifer & Shifer, 1981) answered this question. Original training was carried out in a consistently mapped reaction time search task, with controls utilizing variable mapping. The automation measure was the difference between reaction times to displays of 4 and 16 items.

After consistent training had produced considerable automation (a small difference between display sizes of 4 and 16), a variety of transfer conditions were tested. The targets could be retrained, and the distractors replaced by items that had received (1) varied training or (2) no training. Alternatively, the distractors could be retained, and the targets replaced by items that had received (1) varied training or (2) no training.

All these conditions resulted in considerable (almost complete) transfer of training. The fact that the retention of trained distractors produces good transfer suggests that these items had developed a tendency to attract attention that was lower than for the varied or new items that were used as targets. The fact that new items and varied items differed little in any of these conditions suggests the varied mapping training leaves unchanged the "normal" tendency for an item to attract attention.

Examples of automatic attraction of attention can also be found in paradigms quite different from visual search. For example, Flowers, Polansky, and Keri (1981) used a variant of the partial report paradigm by Sperling (1960). A display of multiletter items was presented to the subject very briefly. Shortly after display offset, a cue was given to report one of the letter strings. When one of the non-cued strings was a word, the report of the cued string was harmed, possibly because the word tended to "pop out" and call attention to itself. Interference and its Absence

If targets come to attract attention (and distractors the reverse) then it is clear that such an automatic process must interfere with other ongoing attentive processing. This is clearly demonstrated in Figure 11.17. On the other hand,
such interference ought to occur only when a target is presented. At other times interference with other processes ought not to occur, even though the requirement to respond to trained targets is in force at all times.

Schneider and Fisk (1982a) tested this possibility in a dual task experiment. The subjects searched through multiple frames. Each frame contained four characters arranged in a square. Subjects carried out two search tasks simultaneously. On one diagonal varied mapping search was required (digits among digits, with the memory set of two items presented before each trial). On the other diagonal, a consistent search was required (letters among digits, any letter constituting a target). In single task control conditions, the displays were unchanged, but only one diagonal was relevant and only one task was required (no targets occurred on the irrelevant diagonal). In all conditions the subject pressed a key after the sequence of 12 displays to indicate the presence of a target. On any trial at most one target could occur. Subjects were well practiced so that in the consistent conditions automatic detection was well developed.

In one version of this study subjects were told to attempt to perform well in both tasks when both were required. Under these conditions, automatic detection was equal in both single and dual task conditions, but controlled search (the varied diagonal) was much worse in the dual task setting. This was true even though no automatic target occurred on the same trial as a varied target. Schneider and Fisk (1982a) hypothesized that subjects might have been allocating some attention to the consistent diagonal even though it was not needed there. They therefore instructed subjects to give primary attention to the varied diagonal, responding to targets on the other diagonal only if one happened to be noticed. The results are given in the left hand panel of Figure 11.16, in terms of the A' performance measure which takes into account both hits and false alarms. On the boundaries of the square are plotted the single task results; in the interior are plotted the dual task results. The three conditions plotted come from three replications using different times per frame. Clearly, both tasks could be accomplished together about as well as when each task was carried out alone. The automatic performance showed what is termed a bias shift: Both hits and false alarms dropped when subjects were told to attend almost fully to the varied diagonal. However, sensitivity, as measured by A', did not change, and was not lower than the single task control. These results stand in sharp contrast to those in the right panel of the figure, in which the subject carried out two varied mapping searches concurrently. Here limited attentional capacity came into play (even though any trial contained at most one target, just as was true in the left hand panel). It seems clear that the subject was actively checking (comparing) the test items in the varied conditions, but was not doing so in the consistent conditions—instead the automatic target called attention to itself.

The Causes of Automaticization

Although it is clear that consistent training facilitates automaticization, there are a good many questions left unanswered by the studies described thus far. For example, how consistent must training be? Schneider and Fisk (1980b) held consistent across trials the number of times various items appeared as targets, and varied the number of times these items appeared as distractors (the stimuli were nine concentric and a multiple frame search task was utilized).

Five degrees of consistency were used: (1) always target, never distractor (consistent control); (2) target twice as often as distractor; (3) target and distractor equally often; (4) target half as often as distractor; (5) target about one seventh as often as distractor (random control). After training, performance was a monotonic function of consistency. Conditions (1), (2), and (3) were all much better than (5), but (4) and (5) did not differ statistically. Examination of the training data suggested that inconsistency both slowed the rate of automaticization and limited the asymptotic degree of automaticism that could be reached (when an item was used as a distractor two times or more often than as a target, detection of that item could not be automated).

An interesting variant on the usual search task may also provide evidence concerning automaticization based on partial consistency: Durso, Cooke, Breen, and Schwanweitz (1976) had subjects search displays of digits for the largest. When B was present, it was always largest; when 1, 2, or 3 were present they were never largest; when intermediate digits were present, the probability they were largest was proportional to their size. Shiffrin and Czerwinski (in press) proposed that digits came to attract attention based on their relative frequency of being largest. The time for attention to settle on the actual largest digit in a display was assumed to be a function of the difference in attention attracting tendencies for the two largest digits in a display (nearly predicting the fact that observed reaction times were faster—the larger was the numerical difference between the two largest digits). This model did a good job of predicting most of the findings, including some that appeared puzzling at first glance. For example, the model correctly predicted targets 4 and 9 to be faster. Target 4 was predicted to be fast because it was guaranteed to have the low strength digits 1, 2, and/or 3 as competitors, whereas target 9, say, would often have the higher strength digit 4 as a competitor.

What is it about a trial that produces automaticization? Searching for and finding an item produces a) automaticization, however, searching for and not finding an item is somewhat harmful compared with not searching for it at all. Other factors affecting rate of automaticization include: second task, B were the less the feature overlap between target and distractor items, 2) Massing or distribution of practice makes little difference. (3) Prior varied training may slow the subsequent rate of consistent learning. (4) Multiple display tasks may lead to faster learning, in terms of trials of practice than single frame tasks. These matters are discussed by Shiffrin, Dumais, and Schneider (1981).

Finally, it may be asked how the development of automatic detection is affected by contextual conditions. For example, can both a consistent task and its reversal be automated if the environmental, task-irrelevant context changes sufficiently between the two situations? Relatively little is known yet about contextual control of automatization (or even about generalizability of automatic detection to related stimuli). Shiffrin and Dumais (1981) obtained one negative result: Three consistent visual search tasks were trained in successive blocks in repeating fashion for many days. In one task, items detected by A were targets with B distractors, in the second task, C targets with A distractors; in the third task, C were targets with A distractors. All three of these did not become automated. The data suggested that one task became automatized, one was entirely non-automatic and the third a mixture of the two. This is rather weak manipulation of context (and perhaps should not even be called a context manipulation); common sense suggests that differences of type of automatization (perhaps even incompatibility) types could be learned in substantially different
contexts, but the relevant research has yet to be carried out.

**Theoretical Interpretation**

The data from consistently mapped search studies of attention behavior support the following model of automatic detection and automatization: When any item or items are presented in a display, each is processed with sets of complementary processes, one a group of automatic processes, and the other a group of attentive mechanisms. The processes and automatic processes may trade information at various levels, but it can be useful to conceptualize any local process as either automatic or attentive. The automatic processes are either innate or have been learned, and do not much partake of capacity limitations: They can operate in parallel with certain other automatic and attentive processes without loss and without interference with those other processes. The attentive processes are limited in capacity and tend to interfere with one another, often leading them to be used successively.

The properties of internal responses that may be produced largely by automatic processes if, say, an alphabetic character is presented include the following: brightness contours, contrast, color, spatial frequency analyses, and other primitive sensory analyses, well-learned responses that are more central than less specific sensory aspects of the "name" of the letter or the "category" of the character may be determined in largely automatic fashion. An internal attention response (perhaps a call to the attention system) will also be produced automatically, though the automatic calls to the attention system will certainly have to compete with the calls produced by other implinging stimuli, external or internal, and the calls produced electively by the subject.

The dual task paradigms of the automatic responses are effective in generating correct responses independent of load. Instead the memory set items and display items must be compared with the use of a limited, perhaps serial, comparison process. The varied practice does not lead to the development of more helpful automatic responses because what may be learned and helpful on one trial will be harmful on the next. For example, an increased tendency to attract attention for a target from one trial will harm performance on other trials when that item becomes a distractor.

On the other hand, when the mapping is consistent, a number of new and helpful automatic responses can and will be learned. For example, target stimuli can develop strong calls to the attention system (and distractor stimuli can develop less strong than normal calls to the attention system); target stimuli can come to elicit category targets; target stimuli can come to elicit internal "target" responses; target stimuli can even come to elicit automatic overt responses (e.g., a particular button press). It should also be emphasized that such automatic responses can be learned not only on the nominal stimuli themselves, but also to the features of those stimuli that are consistently related to target status. Thus if some aspect of the targets as a group distinguish these from the distractors (for example, vertical line segments in all targets but in no distractors) then automatic responses can be attached to those features in addition to, or as an alternative to, the responses to the targets themselves. Whichever type of automatic responses are learned, traditional associative learning mechanisms are capable of subserving the relevant subprocesses of the two conditions.

A model of automatization based on these principles (or similar ones) seems capable of handling the findings from search paradigms (see Shiffrin and Schneider, 1984, for some mild constraints). Within this experimental context, the distinctions between automatic and attentive processes are well defined in both theoretical and empirical terms. To what extent the approach can be generalized to other settings? A partial answer can be found in auditory search tasks, in which similar findings are obtained (Pollack, Lunsman, & Hunt, 1982). However, a switch from the visual to the auditory modality in the same task environment is not a very substantial test of generalization. The dual task paradigms discussed in the first section provide a stronger generalization test. It appears that certain characteristics of automatization that apply to search can be carried over. For example, consistent practice of a task could lead to the development of (partly) automatic processes of overt and covert responses, reducing the attentional demands of that task, and allowing an attention demanding primary task to be carried out near optimal levels of performance. Nonetheless, there are important differences: Attention itself seems to be automatized in the consistent search task, so an irrelevant automatically trained target causes interference with a simultaneous task (see the section on automatization of attention). Why attention can be removed from a secondary task in some settings but not in the search task is a research issue yet to be explored. A more general issue concerns the existence of characteristics that can be used to discriminate automatic and attentive processes in all task settings. Many such characteristics have been proposed and a number of these will be reviewed in the next section.

**Characteristics of Automatic and Attentive Processes**

We shall see in this section that there do not seem to be any simple defining features of automatic and attentive processes that can be applied in complete generality. Nevertheless, the search for such characteristics has generated a very valuable and interesting research in the last few years. Many of the criteria discussed below or are correlated with one another, so certain groups of criteria are discussed together.

**Capacity/Resource Use and Interference**

The fact that attention itself can be automatized raises some problems for criteria based on capacity/resource use, and interference. Because attention is called by targets, the presentation of targets will interfere with other ongoing processes requiring that attention; similarly resources will be utilized since attention to the target will occur. The problem here is locating necessary and sufficient conditions for automatism, or for attentive processes. A process that does not use resources, or does not interfere with other attentive processes, is certainly automatic. Hence such criteria are sufficient, but not necessary. Conversely, automatic processes must use central capacity and must interfere with other attentive processes, hence such criteria are necessary but not sufficient.

The interference criterion is an interesting one: Attentive processes must interfere with other attention processes if they are used, but the interference can be eliminated because the subject can choose not to use the process in question (although performance may drop if this is done). On the other hand, if a process produces interference, which the subject's attempts to eliminate the interference, then the process in question is surely automatic (as was the case in the study whose results are shown in Figure 11.13).

Although we have focused our discussion on search paradigms, the most well known task used to study "automatic" interference is known as the Stroop task (Stroop, 1935; see Dyer, 1973, for one review). The standard task requires the subject to name the ink colors in which a series of words are printed. In one control condition, the words are random, and do not contain any color names. In the interference condition the letters spell a color that is different than the ink color in which the word is printed (e.g., RED printed in blue ink). In the facilitation condition, the word names a color that is the same color in which the word is printed (e.g., RED printed in red ink).

There are many variants of this task: For example, one might have to name the number of digits in a region, when the digits themselves are color consistent with, or inconsistent with, the number present (Morris, 1989); name pictures representing words, with printed words as interfering stimuli (e.g., Luster & Katz, 1981); name letters which in outline, form a larger, different letters (e.g., Hoffman, 1981); name different letters or words (e.g., Eriksen & Schultz, 1970; Shaffer & LaBerge, 1976).

The standard result is that the time to name the color of ink is slowed by incompatibility (and somewhat helped by compatibility), with errors showing a similar pattern. The standard interpretation of interference is that the printed letter name is encoded automatically, despite the subject's attempt to ignore the printing, producing a response tendency that conflicts with the different response required to name the ink color.

Researchers have questioned this interpretation on several grounds. For example, the entire process by which the interference occurs can hardly be automatic, else normal reading would be virtually impossible. The several words in the subject's field of vision would interfere with one another. Perhaps more to the point, the fact that neur...
words produce less interference than color words suggests that the subject's intent to emit color names primes these responses and accounts for the interference they produce. Evidence supporting this view comes from a study in which the subject must emit digit names as well as color names; in such a case printed names of digits produce as much interference with the ink color naming as does printed color words (Neumann, 1984). The idea that attentional control interacts with automatic feature extraction to produce the Stroop effect (see Logan, 1988) is supported on several grounds. For example, matching the ink color to a colored patch does not show the interference from the printed color name, presumably because the translation of the written code to a perceptual one is not as automatic as the transmission of the written code to a verbal one (unless attention is used to facilitate the translation; see Vrzi & Egeth, 1985).

It also appears that the spatial distribution of attention affects the amount of interference. To take one of many examples, Goolkasian (1981) presented a word printed in black at the focus, and a color patch as a target (whose color was to be spoken) either in the focus, or at seven degrees from the focus. The target was presented briefly, and the distractor's onset was varied systematically with respect to target onset. Regardless of stimulus onset synchrony, the false presentation of the target produced large Stroop effects, but parafoveal target presentation produced rather small and irregular effects, primarily facilitating. Apparently the directing of attention to a spatially distant location from the distractor eliminates most of the Stroop interference. Somewhat different studies leading to similar conclusions were carried out by Kahneman and Henik (1981).

Thus there are certainly automatic aspects to the Stroop situation (such as the encoding of the name represented by the printed word, and the inevitable interference that occurs in certain situations), but the magnitude of inhibitory and facilitory effects are determined by certain attentive effects as well. Among these are requirements that the subject intend to emit responses of the type represented by the distractor, and that the distractor appears near the region where the subject is placing his visual attention.

Although much more can be said about the Stroop effect, these results serve to illustrate an important point: certain component processes used to accomplish tasks can be automatic or attentive, but tasks as a whole are accomplished by complex mixtures of automatic and attentive processes operating in concert. Finally, the recent findings concerning awareness and Stroop effects demonstrate an important point. A finding of mandatory interference implies that certain automatic processes are taking place, but not that entire tasks are automatic. The existence of altered conditions in which the interference is eliminated does not imply that automatic processes are not present. The implication is instead that in the new task a crucial link in the sequence of attentive and automatic processes learning to the interference must have been eliminated.

Preparation

In an effort to find a necessary and sufficient criterion one might propose that an automatic process is one that requires no preparation for its operation. In this context, preparation refers to processes carried out before the stimuli requiring a response are presented. For an automatic process, preparation should use no resources, should not interfere with other activities and should require no effort, primarily because active processes in advance of stimulus presentation should not be needed. This definition may be adequate for many automatic processes, including many of those in the search domain, but has difficulty with automatic processes that are initiated by an attentive process. For example, a tennis player might have a choice of two backhands to hit: slice and topspin. Once a shot is chosen, a whole set of (partly) automatic processes may carry the action to its completion, but the actions would not occur without the original choice. If the unit of analysis in question were large enough, then the entire sequence including and ensuing from an attentive act might be considered an attentive process. This would strike most researchers as an overly restrictive position.

At a more molecular level of analysis, a long sequence of processes begun by an attentive choice could be broken into component parts, only the first necessarily being attentive. The process of preparation would not be useful in such a case. Furthermore, a basic issue must be faced: What status should a process have when among its necessary triggering stimuli are used to accomplish tasks can be automatic or attentive, but tasks as a whole are accomplished by complex mixtures of automatic and attentive processes operating in concert. Finally, the recent findings concerning awareness and Stroop effects demonstrate an important point. A finding of mandatory interference implies that certain automatic processes are taking place, but not that entire tasks are automatic. The existence of altered conditions in which the interference is eliminated does not imply that automatic processes are not present. The implication is instead that in the new task a crucial link in the sequence of attentive and automatic processes learning to the interference must have been eliminated.

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Rate of Learning

A somewhat different approach to a criterion involves the speed of learning and unlearning. Automatic processes are generally learned gradually, or if they are already learned, they are difficult to unlearn. Attentive processes can be "turned on" or "turned off" at the momentary whim of the subject. James (1890) conceived of attention in the immediate sense as something "to make us: (a) perceive, (b) conceive, (c) distinguish, (d) remember better than otherwise we could." The "otherwise" refers to the normal automatic processes that would operate without attention. It is interesting that automatization can serve these same functions in the long run, given an appropriate training regimen. Unfortunately, a criterion based on speed of learning is almost impossible to apply in practice. Certain automatic processes may come close to operating in a fashion as little as a single trial (for example, aversion caused by strong negative reinforcements such as strong shocks or negative agents producing taste aversion). Even in the search domain, evidence for automatization has been seen in as few as eight trials (Schneider, 1985).

Depth of Automatic Processing

Preattentive Processes

Many modern attention theorists begin with Broadbent (1958), and including Treisman (1960), Kahneman (1973), and Neisser (1967) among others, have accepted the need for automatic processes but have tended to relegated them to peripheral mechanisms early in the processing stream. These processes have often been called "preattentive" processes, and often are said to be based on analyzers tuned to sensory features on primitive dimensions. No one would disagree that such processes are automatic (in some cases chemical or neural substrates for the analyses have been identified). However, much deeper analysis can also be automatic, as discussed next.

Automatic Processing Based on Semantic Factors

One of the strongest and clearest demonstrations of automatic processing at a "deep" level has been provided by Schneider and Fisk (1984) in the search domain. Subjects were trained in a consistent paradigm to pick out and indicate the position of a target within a display of three words. Before each trial the subject was given a category of words to search for (e.g., weapons). Over trials the number of exemplars seen as targets was limited; for different categories, the number was either 4, 8, or 12. Distractors were words from four other categories. All three categories improved with practice and automatic detection of either the category, the members (4, 8, or 12), or both, appeared to have developed. The fact that improvement with training took place at similar rates for the categories represented by different number of exemplars suggested that the performance was mainly governed by category detection, rather than exemplar detection.

A stronger test of the hypothesis that the category was being detected automatically came from the observation that the subjects from the four previously trained categories were introduced. Positive transfer to these new items was high (about 92 percent). The most plausible hypothesis is clear: When a new item was presented in a display its category was generated automatically, and search could be made of the items previously trained categories. The category response in turn generated another response one learned during consistent training, probably a response causing attraction of attention (as in the case with item automatization). In the control conditions using varied mapping (is which performance was much worse) each test item presumably also had its category extract automatically, but these category names had to be compared serially to the target category.

An even stronger demonstration of detection based on automatic category extraction came from a condition using multiple frames and lv simultaneous tasks. In the center of each display a word appeared and in the periphery, digit appeared. For word detection, the category name was specified before each trial in a consistent manner. Simultaneously the subject searched for target digit specified before each trial in a variable manner. After training subjects appeared capable of carrying out both searches simultaneously, presumably because the word task was automatized. Then no
exemplars from the trained categories were introduced. Even though the subjects were carrying out an attention-demanding search for digits simultaneously, the new exemplars were detected almost 83 percent of the time. Comparison with various control conditions confirmed the conclusion that the items presented for test had their category membership extracted automatically, and that the category label then attracted attention automatically, on at least a large proportion of the trials.

Such results imply that depth of processing is not a criterial difference between attentive and automatic processing. Indeed, there is reason to believe that at least some processes at almost any depth can be automated, given appropriate conditions. Nonetheless, as Bryan and Harter (1980) suggested, later developing automatic processes probably build on a base of already developed automatic processes, so the likelihood of automation is probably less the deeper the process is in question. Furthermore, there is every reason to believe that certain types of peripheral mechanisms are structurally predisposed to be automatic even at birth or shortly thereafter, regardless of learning.

Control of Processing Depth

Given that relatively late and central stages of processing can be automated, two related questions arise: Can processing be made more deep, or more shallow, through application or attentive resources? That processing can be extended through application of attentive resources has never been in doubt (e.g., the extraction of meaning from poetry). However, a distinction must be made between a direct application of attentive resources (e.g., serial comparisons during search tasks), and modification of automatic processing through attentive control, which is an indirect application of attentive resources. This latter issue has undergone considerable scrutiny, perhaps because some theorists feel that automatic processes ought not to be modifiable. The question of modifiability will be discussed in the next section (and also later in the paper during sections on locus of control and locus of limited capacity). For present purposes, it should be noted that processing depth would not be a suitable criterion for discriminating automatic and attentive processes, whether depth of processing is modifiable or not.

Modifiability of Automatic Processing

Automatic processes may sometimes have consequences that are impossible to eliminate through attentional control (e.g., the interference seen in Figure 11.5), see also the section above on the spatial effect). Nonetheless, most automatic processes may be partially controllable and some automatic processes may be highly controllable through attentive means, especially when such attentional processing provides some of the environmental stimuli that trigger the operation of the automatic process. That is, the subject can through attentive means control the input to an automatic process, thereby exerting control over the process itself. An extreme example would be an eye movement to move a character in the visual field to a region of different acuity, thereby controlling the automatic processing it is given. (Related to this notion is the possibility that some automatic processes might usually or always be initiated by attentional processes.) One might think it would be useful to draw a distinction between input control of automatic processes through the inputs it receives in advance, and more direct control of an ongoing automatic process, but such a distinction is too subtle at the present theoretical and empirical development of the field.

Given that the possibility of direct or indirect modifiability of automatic processing is accepted, it is still useful to cite instances in which attention can influence processes that appear on the face of things to be quite peripheral and automatic. Consider, for example, the eyblinking reflex studied by Graham and her colleagues (e.g., Graham, 1975; Bohlin & Graham, 1977; Silverstein, Graham, & Bohlin, 1981; Bohlin, Graham, Silverstein, & Hackley, 1981). The blink reflex is a startle response to sudden auditory or visual stimuli. The reflex is triggered by the brainstem (e.g., occurs in decorticat animals), and it is assumed to be a good candidate for an automatic process. Nevertheless a number of studies in animals and adult humans have shown this reflex is modifiable by attentional control. A representative study using infants (16 weeks) was published by Anthony and Graham (1983). The infant was given a foreground stimulus for five seconds to attract attention to a sensory modality. The foreground stimulus was either interesting (a face or a tone) or dull (a blank side or a tone). Then a sudden light flash or noise was introduced. Blinks were larger when the modality of foreground and stimulus matched when they mismatched. This effect was larger for interesting foregrounds. The conclusion reached by Anthony and Graham seems reasonable. The attention to modality produced by the foreground was caused a modification of a relatively peripheral and low level automatic process. It seems highly likely in this case that the movement of attention to the appropriate modality was an automatic response to the foreground stimulus (as, for example, the attention shift to an irrelevant automatic target was involuntary in the study of Figure 11.5), but this reasoning only confirms that an attentional shift produces the changes observed in the blink reflex. Indeed, in other studies using adults, similar changes were induced by instructions and other means.

Results like these suggest that there can be some degree of attentional control of automatic processes, but they leave open the degree to which most automatic processes are attentionally modifiable. Johnston and Dark (1982) contrast two views: (1) Extra perceptual: perceptual processing is automatic and unaffected by attention; attention acts directly by supplementing automatic processing. (2) Intrapercptual: automatic perceptual processing is modifiable by attention; the more attention directed to an item the more perceptual processing occurs. Convincing evidence distinguishing these views is hard to find.

Consider the study reported by Johnston and Dark (1982); Subjects listened to lists of pairs of different words presented dichotically, one pair every 1.5 seconds. The subject's main task was to determine if the names of states in the focused condition were presented to a known, designated ear. In the divided condition, these targets were divided 33 and 34 between the two ears. Simultaneously with this task, the subjects viewed a screen: whenever a word was presented visually, the subject named a free associate and then answered their auditory task.

The visual words were homographs (two meanings). Just before the visual word test, and just after, two of the non-target auditory words were primes that biased the subject toward perceiving one of the two meanings of the visual homograph (e.g., the visual test word bark would be paired with successive auditory words, either wood and chips, or growl and noise). The two primes occurred successively on one of the two ears.

The results showed the usual effect of focusing attention: Target detection (states) was superior in the focused attention condition (in visual search terms, the task varied "display" size). It is unclear to what extent this primary auditory detection task was accomplished by automatic detection. In any event, the question of present interest concerns processing of the nontargets, as assessed by responses to the visual probe: In fact, a meaning consistent with the biasing words was obtained most often when these biasing words were on the attended ear in the focused condition and least often when these words on the unattended ear in the focused condition; the divided condition was intermediate. Johnston and Dark (1982) argued that automatic perceptual processing of the auditory words was directly affected by the degree of attention paid to the ear containing them (as assessed by the effects produced by the biasing words). Unfortunately, as the authors admit, the same results would be predicted if the biasing effect was caused by the amount of direct processing the words. This problem (or similar ones) affects most of the studies in this area, so at the present time, the degree to which automatic processing is affected by attention is an unsettled issue.

Effort

Effort has long been thought related to attention, the term "effortful processing" being used by Hasher and Zacks (e.g., 1979) to refer to attentive processing. If effort is defined only subjectively, then this definition is unlikely to be of much help. If effort is defined in terms of objective measures, these measures may lead to empirical tests; indeed many of these are discussed in this section. It must be admitted that data are impressively obvious difference between processes researchers would like to call automatic and attentive. Nevertheless, some nagging problems remain: (1) How does one deal with "automatic" processes that require an attentive process to trigger? (2) If attention is called automatically, some effort might be engaged. (3) When attentive processes become very easy, effort might tend to drop below noticeable threshold.

In an effort to assess the effort required of
words produce less interference than color words suggests that the subject's *intention* to emit color names primes these responses and accounts for the interference they produce. Evidence supporting this view comes from a study in which the subject must emit color names as well as color names in such a case printed names of digits produce as much interference with the ink color naming as does printed color words (Neumann, 1984). The idea that attentional control interacts with automatic feature extraction to produce the Stroop effect (see Logan, 1988) is supported on several grounds. For example, matching the ink color to a colored patch does not show the interference from the printed color name, presumably because the translation of the written code to a perceptual one is not as automatic as the transmission of the written code to a verbal one (unless attention is used to facilitate the translation; see Vrishi & Egoth, 1985).

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Although much more can be said about the Stroop effect, these results serve to illustrate an important point: certain component processes used to accomplish tasks can be automatic or attentive, but tasks as a whole are accomplished by complex mixtures of automatic and attentive processes operating in concert. Finally, the recent findings concerning the Stroop effect demonstrate an important point. A finding of mandatory interference implies that certain automatic processes are taking place, but not that entire tasks are automatic. The existence of altered conditions in which the interference is eliminated does not imply that automatic processes are not present. The implication is instead that in the new task a crucial link in the sequence of attentive and automatic processes learning to the interference must have been eliminated.

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**Depth of Automatic Processing**

**Preattentive Processes**

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A stronger test of the hypothesis that the category was being detected automatically came from a transfer test: New exemplars from the previously trained categories were introduced. Positive transfer of the new category was high (about 92 percent). The most plausible hypothesis is clear: When a new item was presented in a display its category was generated automatically (as would normally be the case even without training in this task). The category response in turn generated another response, one learned during consistent training, probably a response causing attraction of attention (as in the case with item automatization). In the control conditions using varied mapping (in which performance was much worse) each test item presumably also had its category extracted automatically, but these category names then had to be compared serially to the target category.

An even stronger demonstration of detection based on automatic category extraction came from a condition using multiple frames and two simultaneous tasks. In the center of each display a word appeared and in the periphery, digits appeared. For word detection, the category name was practiced before each trial in a consistently mapped fashion. Simultaneously the subject searched for target digits specified before each trial in a variably mapped fashion. After training, subjects appeared capable of carrying out both searches simultaneously, presumably because the word task was automatized. Then new
Exemplars from the trained categories were introduced. Even though the subjects were carrying out an attention-demanding search for digits simultaneously, the new exemplars were detected almost 82 percent of the time. Comparison with various control conditions confirmed the conclusion that the items presented for test had their category membership extracted automatically; and that the category label then attracted attention automatically, at least a large proportion of the trials.

Such results imply that depth of processing is not a criterial difference between attentive and automatic processes. Indeed, there is reason to believe that at least some processes at almost any depth can be automatized, given appropriate consistent training. Nonetheless, as Bryan and Harter (1899) suggested, later developing automatic processes probably build on a basis of already developed automatic processes, so the likelihood of automatism is probably less the deeper the process is in question. Furthermore, there is every reason to believe that certain types of peripheral mechanisms are structurally predisposed to be automatic even at birth or shortly thereafter, regardless of learning.

Control of Processing Depth

Given that relatively late and central stages of processing can be automatized, two related questions arise: Can processing be made more deep, or more shallow, through application or attentive resources? That processing can be extended through application of attentive resources has never been in doubt (e.g., the extraction of meaning from poetry). However, a distinction must be made between a direct application of attentive resources (e.g., serial comparisons during search tasks), and modification of automatic processing through attentive control, which is an indirect application of attentive resources. This latter issue has undergone considerable scrutiny, perhaps because some theorists feel that automatic processes ought not to be modifiable. The question of modifiability will be discussed in the next section (and also later in the paper during sections on locus of control and locus of limited capacity). For present purposes, it should be noted that processing depth would not be a suitable criterion for discriminating automatic and attentive processes, whether depth of processing is modifiable or not.

Modifiability of Automatic Processing

Automatic processes may sometimes have consequences that are impossible to eliminate through attentional selection (e.g., the interference seen in Figure 11.15, are also the section above on the Stroop effect). Nonetheless, most automatic processes may be partially controllable and some automatic processes may be highly controllable through attentive means, especially when such attentive processing provides some of the contextual stimuli that trigger the operation of the automatic process. That is, the subject can control means not the input to an automatic process, thereby exerting control over the process itself. An extreme example would be an eye movement to move a character in the visual field to a region of different acuity, thereby controlling the automatic processing it is given. (Related to this notion is the possibility that some automatic processes might usually or always be initiated by attentive processes.) One might think it would be useful to make a distinction between indirect control of an automatic process through the inputs it receives in advance, and more direct control of an ongoing automatic process, but such a distinction is too subtle at the present technical and empirical development of the field.

Given that the possibility of direct or indirect modifiability of automatic processing is accepted, it is still useful to cite instances in which attention can influence processes that appear on the surface of things to be quite peripheral and automatic. Consider, for example, the eyeblink reflex studied by Graham and her colleagues (e.g., Graham, 1976; Rohlin & Graham, 1977; Silverstein, Graham, & Rohlin, 1981). The blink reflex is a startle response to sudden auditory or visual stimuli that is governed by the brainstem (e.g., occurs in decorticate animals). This response seems to be a good candidate for an automatic process. Nevertheless a number of studies in animals and adult also the active show this reflex is modifiable by attentive control. A representative study using infants (16 weeks) was published by Anthony and Graham (1983). The infant was given a foreground stimulus for five seconds to attract attention to a sensory modality. The foreground stimulus was either interesting (a face or a tune) or dull (a blank side or a tone). Then a sudden light flash or noise was introduced. Blinks were larger when the modali-
ties of foreground and stimulus matched when they mismatched. This effect was larger for interEFAULT ATTENTION

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ties that had in mind one of the two ears.

The results showed the usual effect of focusing attention: Target detection (states) was superior in the focused attention condition (in visual search), and the task varied "display" size. It is unclear to what extent: this primary auditory detection task was accomplished by automatic detection. In any event, the question of present interest concerns processing of the non-targets, as assessed by responses to the presence of the visual noise. The biasing words was obtained most often when these bisecting words were on the attended ear in the focused condition and least often when these words on the unattended ear in the focused condition; the divided condition was intermediate. Johnston and Dark (1982) argued that automatic perceptual processing of the auditory words was directly affected by the degree of attention paid to the ear containing them (as assessed by the effects produced by the biasing words). Unfortunately, the results did not support this, but the same results would be predicted if the biasing effect was caused by the amount of direct, attentional processing given to the biasing words. This problem (or similar ones) affects most of the studies in this area, so it is present in most of the studies, the degree to which automatic processing is affected by attention is an unsettled issue.

Effect

Effort has long been thought related to attention, the term "effortful processing" being used by Hasher and Zacks (e.g., 1979) to refer to atten-
tion activity. If effort is defined more specifically, then this definition is unlikely to be of much help. If effort is defined in terms of objective measures, these measures may lead to empirical tests; indeed, many of these are discussed in this section. It must be admitted that different types of effort are the most introspectively obvious difference between processes researchers would like to call attentional and attentional. Nevertheless, that automatic processes might play a role in this is not something that attentional processes become very easy; effort might tend to drive below noticeable threshold.

In an effort to assess the effort required
processing, Posner and his colleagues developed what is known as the "probe" technique (e.g., Posner and Boies, 1971). The subject is asked to carry out a primary task, such as visual letter matching, and at various times after task onset is occasionally interrupted by presentation of a probe stimulus, such as a brief tone. Whenever the probe occurs, the subject attempts to respond to it as quickly as possible. It is reasoned that responding to the probe should utilize at least some capacity and therefore that speed of responding to the probe should be inversely related to the momentary effort being required by the primary task. Posner and Boies (1971) used this approach when the primary task was the matching of sequentially, visually presented letters. They concluded that encoding of at least the first letter was automatic and effortless because probes just after the onset of the first letter were responded to quite quickly relative to, say, probes during the intertrial interval. Posner and Klein (1975) extended these findings and came to similar conclusions (see also Posner, 1978, 1962).

The conclusion that letter encoding is effortless, however, was a bit premature. Ogden, Martin, and Paap (1980), Paap and Ogden (1981), and Jacobson, Forster, Goldwater, and Waisgerber (1983) utilized improved methodology with better controls and came to the opposite conclusion. Probe times were indeed increased by encoding demands, and this interference was present even when letters were presented that were to be ignored. Thus these authors concluded that encoding of letters utilized capacity and did so in obligatory fashion.

Several issues of present importance are raised by these results. The finding of interference caused by a presented stimulus is not necessarily evidence against automatism (we saw interference in a search task, in Figure 11.18, when the stimulus causing the interference had been trained to attract attention). Indeed, the obligatory nature of the interference suggests that processing was automatic. One possibility is that presentation of a letter engages the attention system, and calls for attention, thereby producing the observed interference. Do the same results obtain if the letter is required for encoding? Probably not, unless a call for attention caused by presentation is interpreted as a source of effort. Thus even though attentive processes may be characterized by an output of effort, the tasks used to assess such effort (such as the probe technique) may give misleading results. They may give the appearance of effortful processing, through automatic activation of the attention system itself, in cases that most people would prefer to classify automatic.

Precedence and Speed

It is sometimes thought that automatic processes should precede attentional processes in an processing sequence, and should operate more quickly than attentive processes. Neither of these criteria are essential, as we have indicated in earlier sections, but evidence that bears on this issue comes from: what has been an important paradigm in the study of attention and automatism: the priming paradigm.

There are many variants of priming tasks. Usually some decision (e.g., Is the stimulus a word? Was the stimulus on a recent list? Is the stimulus an animal?) is to be made as well or as quickly as possible about a target stimulus. Shortly before the target is presented, a prime is presented. The prime may occasionally be informative concerning the decision to be made but often is completely irrelevant. However, unknown to the subject, the prime is semantically related to the target in the key experimental conditions.

Consider tasks with words and nonwords as stimuli: the subject is asked to decide whether the target is a word (i.e., lexical decision). The key result is as follows: when the prime is semantically related to the target (e.g., water–ICE) then the response to the target is facilitated, compared with controls using "neutral" primes consisting of a row of Xs. Sometimes there is also an interference. The neutral primes lead to better performance than an "unrelated" word prime. It is usually assumed that relatedness information is automatically activated and resides in short-term memory until it affects the target decision, or that the prime begins a process of automatic spreading activation that pre-activates the target, thereby affecting the decision. Whether the activation is truly automatic is a question that arises in many of these paradigms.

Posner and Snyder (1975a, b) proposed a theory and collected certain data suggesting that a prime leads to automatic, fast, activation of related items, thereby producing better processing of these related items when they are targets. In addition, a prime may lead to concomitant, attentive processing which is slow and produces both costs and benefits, depending on task demands and stimulus factors. This idea was supported by the early investigators mentioned in the first section (e.g., Solomons & Stein, 1969; Donwey & Anderson, 1915—though these researchers eventually decided against using such a criterion).

The Withinness criterion has been used in several interesting studies to infer the existence of automatic processing. An item is presented very briefly and then followed by a masking stimulus. The conditions are such that the subject cannot report the item presented even though attention is focused upon it. This stimulus is called the prime, and is followed within a few seconds by a target that is not masked. The target item is classified in some fashion, perhaps as a word or nonword. In some studies the masked prime that cannot be reported affects processing of the target. For example a word prime may speed a decision about a word that is semantically related to the prime (e.g., Marcel, 1979, 1980; Fowler, Wolford, Siple, & Tassinary, 1981). Such effects must be automatic if "awareness" is used as a criterion for automatism. Nonetheless, attention is certainly focused on the prime that is masked, and in many studies, subjects report an impression that the prime is perceived but then lost from memory when the mask occurs. Thus it would be premature to assume that automatic processing plays no role in the observed priming effects. (A related effect occurs when the prime is not masked, but presented several times at durations such that later yes-no recognition judgments are at chance levels. In these cases the prime itself is then used as a target and subjects like it more than a control word, as reported by Kuntz-Wilson & Zajonc, 1980, or think it brighter than a control word, as reported by Mandler, Nakamura, & Van Zandt, 1985).
exists that a more sensitive test could show relatively long lasting changes in memory as a result of an "unaware" prime. Such effects have been reported and are reviewed by Bargh (1984; see also the first section).

Despite the attractiveness of the "awareness" criterion, it has a number of problems. Awareness is defined by the subject's memory. Sometimes, it may be "aware" at one time but then forgotten within a few hundred milliseconds (as suggested by the rapid sensory forgetting seen in studies like those of Spelke, 1960). Related to this is the possibility that some attentive processes operate so quickly that awareness of the components of the process is low (e.g., the comparisons used in varied-mapping search tasks). Conversely, because at least some automatic processes attract attention, they can produce awareness (at least shortly after the fact). For these and related reasons, the consciousness criterion is at best of very limited usefulness and generality.

Control, Intentionality, and Parameter Specification

Shiffrin and Schneider (1977) called attentional processes "control processes." This seems a crucial characteristic, but there are a few problems: (1) Some automatic processes may be triggered directly or indirectly by attentive processes, thereby requiring control and intentionality. (2) Some automatic processes may trigger attentive processes (such as automatic calls to the attention system). (3) Some attentive processes (such as the comparison process in search tasks using varied mapping) operate so quickly that the moment-to-moment details may be difficult to control.

Neumann (1984) has proposed a definition for automatic based on parameter specification: A process is automatic if its parameters (process variables whose values must be specified for the process to operate) are specified by (1) skill and (2) input information. When this is not possible then attention comes into play to specify the remaining needed parameters. In this view, control of automatic processing is vested in incoming environmental information and prior learning (or genetically predisposed structures), a view basically consistent with the control criterion, and sharing its problems. Perhaps most crucial is the definition of input: if internal states produced by attentive processes are allowed to be part of the contextual stimulus environment that triggers an automatic process, then the parameter specification criterion (and the control criterion, as well) does not provide a useful distinction in all settings.

Level of Performance and Parallel Processing

Although automatic processing is often thought of as unlimited, there are many limitations on both the performance level that is achievable, and the ability to carry out automatic processes simultaneously without cost. Clearly, whenever two automatic processes share some subprocesses or component in incompatible fashion, there must be interference. For example, if one automatic process involves an eye movement to the right, and another an eye movement to the left, both cannot occur together. More subtle examples occur as well. Shiffrin and Schneider (1977, Experiment 4c) carried out a search study using a multiple-frame design. On each four item display one diagonal was relevant and one irrelevant, consistent mapping occurred on the relevant diagonal. When a (automatic) target occurred on the relevant diagonal, an identical (albeit irrelevant) target on the irrelevant diagonal in the same frame cause a small drop in detection. A similar result occurred in a task in which all four locations in each display were relevant, but two identical targets would occur together in the same display. In both cases, there may have been a competition between two items both demanding attention, but this is an unlikely explanation, because two nonidentical automatic targets do not lead to a similar performance deficit. Schneider and Shiffrin (1977) suggested that both items tend to be attended and accentuated in short-term memory, but that in a multiple frame task the only lasting and useful memory representation is a positionless central one. When two targets are different, the central representations are different; when they are identical, there may be only one central representation, leading to difficulty in judging either the number presented or the position of origin. (See also Erikson & Erikson, 1974, and the section on the Stroop effect, for related research).

Automatic processing in parallel may be limited by demands for common pathways or physical structures. In other cases, parallel operation is impossible because automatic processes occur in chains, the output of one providing some of the necessary input for the next. Thus while the observation of parallel, independent processing may allow an attentive processing hypothesis to be ruled out, the failure of this criterion to hold does not rule out automatic processes. Level of performance of automatic processes is limited by what Neumann and Bobrow (1975) have termed a data limitation (as opposed to a process limitation). When the inputs to an automatic process are too weak or impoverished to trigger the process fully or correctly, then poor performance will result. An example is seen in Figure 11.12 in the left hand panel. At brief display times, false alarms begin to rise, presumably because the features extracted from the display are improved.

Of course, data limitations should apply equally whether the subsequent processing is automatic or attentive, so it is sometimes thought that appropriately trained automatic processing must be superior to attentive processing. However, the advantage of automatic processing lies in the relative independence from effects of load. When the load is small, there is no reason to expect an inherent advantage for automatic processing, and the opposite may be true. For example, in many consistent search tasks, the set size function shows superior performance at small loads even after extensive training (e.g., Ericsson, 1972b; Shiffrin & Durais, 1981). This result may be obtained because attentive processing is used at small loads in parallel with automatic detection. The attentive processing might be often superior at small loads to produce the observed advantage.

Memory Effects

Awareness and retention are related criteria. As Downey and Anderson (1971) noted, their retrospections sometimes showed no awareness, but they felt this was often due to forgetting of an original awareness. The memory criterion is based on the assumption that attentive processing should lead to observable retention, whereas automatic processing may sometimes lead to no retention.

Fisk and Schneider (1984) provided evidence from a multiple-frame search task. Each display consisted of a word presented at the point of fixation, and digits presented in a square at rounding the word. In various conditions, stimuli were induced to attend to the words at varying degrees. On a later recognition test stimuli were asked to give frequency estimates for the test words; these had been presented either 0, 5, 10, or 20 times. Estimation was worse, the less attention was given to the words. In fact who subjects were told to ignore the words and carry out a digit detection task only, they remember nothing about the words, even though they appeared at the center of fixation.

In a second study, subjects carried out digit detection, but simultaneously picked out word of a given category that appeared in the displays. After much training the category task became substantially automatic. Then new members of the trained category were introduced, a new as well as new distractors (from other categories). Substantial numbers of the new targets were detected, even though an attention demanding digit task was being carried out simultaneously. Thus the subjects were analyzing words automatically up to the category level, at least on most trials. Then recognition and frequency judgments were obtained for the new distractor words used in the transfer session. These judgments were not dependent on the frequency of presentation over a range of 1 to 20. Furthermore, the presented items were only slightly discernable from non-presents items (force choice recognition probability was .55, when .5 is chance, and d' was equal to .19). These small effects could have been due to some attention given inadvertently to the words, even though it was not necessary. Thus recognition of unattended words seems to be at least pood and possibly missing, even when those words are being analyzed automatically to the category level.

It may be that a different and/or more sensitive test could bring to light some modifications of memory produced by automatic processing of the type studied by Fisk and Schneider.

1The present results have another implication that bear of claims for automatic processing. Heiser and Zacks (1979) and Zacks, Heiser, and Sarni (1980) have argued that encoding frequency is automatic. Although their results demonstrate that encoding of the frequency variable is somewhat different than for many other variables, the Fisk and Schneider (1984) results make it unlikely that encoding is encoded automatically according to the criteria we have been discussing.
Eich (1984) demonstrated this point. Subjects listened to an interesting story presented to one ear, and shadowed it (repeated it aloud). During this shadowing, pairs of successive words were presented to the other ear (at a somewhat lower loudness). Each pair consisted of a modifier and a homophone, the modifier blurring the less common interpretation of the homophone (e.g., taxi-FARE). Subsequently subjects were tested for their ability to recognize (pick out the presented homophones from new ones), and also for their ability to spell auditorily presented homophones.

The recognition results confirmed the findings of Fisk and Schneider (1984). The probability of judging a homophone to have been presented was .385 when the test homophone had been presented and .383 when it had not; the homophones could not be recognized. Nonetheless, the spelling chosen for a presented homophone was more often in line with the less common interpretation than was true for nonpresented homophones (.388 vs. .255). Thus even though recognition was at chance, presumably because attention had not been given to the nonshadowed items, automatic semantic processing took place to some degree for those same items, causing (automatically) the interpretation of the homophone to be reversed. (This can be attested at Lewis, 1972; Treisman, Squire, & Green, 1974; Johnston & Heins, 1975; MacKay, 1973; Nowstead & Dennis, 1979; Cortein & Wood, 1972). It should be noted that the biasing effect on spelling can be greatly enhanced by application of attention (Eich, 1984; see also Jacobs & Wapner, 1988).

As interesting as are these various memory findings, memory effects do not appear to lead to a useful criterion. It is far from clear that attentive processing must lead to observable retention, and, on the other hand, automatic processing may have some effects on memory, depending on the type of test that is used.

Partial Automation

In most cases, processes will not be practiced to the point of reaching their maximum degree of automation (or performance, if those are not equivalent). The status of processes before asymptotic levels are reached is not clear. It is possible that a process is either automatic or not, and that practice merely increases the probability of the former. Perhaps this view could be defended if the units of analysis are extremely small, but it seems more likely that performance and automation both improve gradually with consistent practice.

Certain data support the gradual view. For example, in search tasks, the probabilistic mixture model predicts that at any stage of training the set size function should be linear (with a slope that decreases with practice). This prediction is based on the assumption that whenever the automatic process is triggered, the set-size function will be flat, and fast. On the other hand, one version of the gradual model assumes that the automatic process always operates in parallel with the serial comparison process, and is a flat function of set size, but with a speed that gradually improves with practice. If so, the set size function should have two limbs: one with normal slope at small set sizes (due to serial comparisons finishing first), and then a flat portion at larger set sizes (due to automatic detection finishing first). The break point should move to smaller set sizes as automatic detection becomes faster. In practice, such a two limbed function might well appear curvilinear, due to “noise” affecting the predictions. The data do seem consistent with this version of the gradual model, but more work is needed. The model typically become curvilinear with decreasing “slope” (e.g., Kristofferson, 1972b) or exhibit two limbs with a decreasing break point (e.g., Ellis & Chase, 1971). It should be emphasized, however, that this reasoning applies only to these versions of the gradual and all-set-size models; distinguishing between more general classes of these models would be much more difficult.

Overview: Criteria for Automatic and Attentive Processing

Most researchers and theorists agree that a distinction between automatic and attentive processes is useful, necessary, and valid, notwithstanding a good deal of controversy concerning the characteristics and roles of these processes. In the domain of search tasks, a breakdown of processes into automatic and controlled components is well advanced, and a good deal is understood concerning the properties of these processes and the nature of their development. However, automatic and attentive processes in search are at most only occasionally used in other tasks. Attempts to define necessary and sufficient criteria to distinguish automatic and attentive processes in complete generality have not yet proven successful. Certain sufficient criteria appear at first glance to be available for automatic and attentive processes: if these processes and task components could be identified unambiguously. However, even in these cases, different answers may be obtained when the size of the unit of analysis is changed. Furthermore, in practice, many processes that have the potential to become fully automatic will have been trained only to some degree of partial automation.

It seems likely that future progress will take place on two fronts: (1) The concepts of automation and attentive processing will be further refined and broken down into subcategories, each of which can be defined more generally and rigorously than is possible globally. (2) Formal, quantitative, or simulation models will be developed for particular classes of tasks, the roles of automatic and attentive processes being precisely defined within the model. Developments of this second kind are currently taking place, and as they continue we can expect to learn a good deal about the roles of automation and attentive processing within certain restricted task domains. An example in the search domain is the recent simulation model by Schneider (1985).

SELECTIVE ATTENTION

In the following sections, we shall deal with the nature of attentive processes when automatic processing is not playing an important (or differential) role. There are many important questions. For example: What are the limitations of systems? How can attention be acquired? How finely can attention be focused? What is the nature of attentional bottlenecks and where in the processing system are they to be found? On what may attention be focused? How does attention help stimulus features: coherence into organized entities? What are the different roles of attentional processes? A variety of theoretical disputes have arisen concerning these questions and there answers. In the remainder of this chapter we shall attempt to present some of the more important issues and data bearing on them.

Limitations of Attention

In varied mapping search tasks we have seen a strict limit upon attentional resources. Single frame tasks show that each additional comparison requires on the average a fixed amount of time to be accomplished (about 40 ms in the case of simple memory search). This limitation may explain performance in multiple frame tasks as well. Since the frame time is fixed, the average number of comparisons that can be accomplished per frame is fixed; thus the chance of completing the key comparison that produces a match decreases as load increases. It may well be the case that a mechanism like this produces limitations of attention in a much wider class of target-detection paradigms, as well. Before considering the possible bases for attentional limitations, however, a certain amount of terminology is needed.

Limitations of attention are conveniently classified into two forms: divided and focused. In divided attention paradigms the subject is asked to spread attention over as many stimuli, or potential stimuli, or sources of stimuli, as possible. Limits are seen because not many things can be attended at once. The analogy of a cocktail party is often used by example of one can attempt to listen to multiple conversations simultaneously, but attentional limitations strictly limit one’s ability to do so. In focused attention paradigms the subject attempts to place all available attention on just one stimulus, type of stimulus, or source of stimuli, ignoring and/or excluding all other inputs. In the cocktail party analogy, one attempts to attend to just one conversation, but may find it difficult to do so because of distraction from other conversations. There are, of course, a variety of paradigms lying somewhere between these two extremes. For example, in many shadowing studies, the subject attempts to repeat aloud stimuli presented to one ear, presumably focusing attention on that ear, but nevertheless tries to detect signals on either or both ears, providing some incentive to spread attention. In the cocktail party analogy, one might be attending to one conversation but trying to remain alert to the mention of some important matter in another
conversation. These issues and many related ones will be the topics of the following sections.

Dividing Attention

As a general rule, subjects find it extremely difficult to divide attention. When there are more tasks to be carried out, more stimuli to be attended, more potential stimuli to be monitored, or more attributes to be attended, performance is reduced. There are exceptions, of course, as indicated earlier in this chapter, but many, and possibly all, of the exceptions may be due to the operation of automatic processes.

Kahneman (1973) has suggested that the exceptions may be related to effort. Dividing becomes easy when the total effort required and/or expended becomes low. If effort is determined by task demands and difficulty then this view is virtually correct by definition. Furthermore, although differential allocation of effort across conditions or tasks might account for changing performance levels, such a possibility seems rather more likely in uncontrolled natural settings. In the laboratory, the experimenter generally attempts to see that the subject is performing at the highest possible level in each condition. Finally, it should be noted that automatization will usually not only improve performance, but also lead to a lessening of effort, defined by either objective or subjective measures. Thus automatization could well explain much of the phenomenon that the effort hypothesis was designed to handle. For these reasons we shall not discuss the effort hypothesis in any detail in this chapter.

We shall not try in this section to review studies purporting to show an ability to divide attention successfully, since many if not all the traditional studies of this sort can be reinterpreted in terms of automatization. Examples were discussed in the preceding sections. Very recently, studies purporting to show multiple central resource pools have begun to appear. These will be discussed in a later section.

Automatization aside, there are situations where attention may be divided more easily than others, and situations in which competing demands are allocated resources differentially. Proper measuring of attention demands, and attention sharing, requires fairly sophisticated techniques of data collection and analysis. These methods are becoming an important part of modern attentional research and are reviewed next.

Performance-Resource Functions

Norman and Bobrow (1975) introduced the notion of a performance-resource function (PRF). It is a hypothetical function giving performance as a function of resources invested in the task. Presumably the remaining resources are either withheld by the subject, or are used to carry out some other task and to manage the carrying out of the two tasks together. The demands of managing two or more tasks together are termed a concurrence cost by Navon and Gopher (1979). Figure 11.17 illustrates some PRFs. For the sake of this example, we assume that the other tasks, if any, do not affect the PRF for the task in question, except by determining the proportion of resources given on the horizontal axis. It is also assumed in this example that there is just one pool of resources. (If there were more than one, the PRF would be multidimensional, one dimension for each resource; the PRF would give performance for each combination of resource values.) Figure 11.17 gives three possible PRFs: Performance in curves B and C improves with resources up to a point, but then reaches asymptote. The asymptote is a data limited region, where the information provided to the decision system from automatic perceptual mechanisms is impoverished; in this region extra resources do not help because the system is acting optimally on the provided data. The PRF C shows that better data is being provided to the system than is the case in B. Since the B and C asymptotes are reached at the same investment of resources, it could be argued that both processes utilize resources in similar fashion. The PRF A never does reach asymptote. The data provided in this case may or may not be impoverished, but in either event, the process in question is so difficult that the best level of performance potentially available is not reached even when 100 percent resources are invested. It is possible that some automatization could occur with practice, and alter a PRF like A into one like B or C.

These functions are hypothetical because, in practice, they are produced by experimentally varying the investment of resources in some other task, a task that could interact with the first in ways other than diversion of attentional resources. (Wickens, 1984, reports that a subject simply instructed to utilize different degrees of resources in a task can produce PRFs like those depicted in Figure 11.17. However, there are obviously other ways than resource limitations to explain such a finding, such as compliance with demand characteristics after decision making has made full use of resources.)

Attention Operating Characteristics

Again hypothetically, suppose there are performance-resource functions for two tasks, as illustrated in Figure 11.18a. Suppose these tasks are carried out together and do not interfere with one another. From "Processing Resources in Attention" by C.D. Wickens in Varieties of Attention (p. 69), R. Parasuraman and D.R. Davies (Eds.), 1984. Orlando, FL: Academic Press. Copyright 1984 by Academic Press. Reprinted by permission.

The joint performance function is known as an attention operating characteristic (AOC; Kinchla, 1969, 1980; Sperling, 1975) or equivalently as a performance operating characteristic (POC; Norman and Bobrow, 1975; Navon and Gopher, 1979). Curve II in the lower left of Figure 11.18 illustrates what sort of AOC could be expected if neither task utilizes resources needed by the other. An empirical example of this type from Schneider and Fisk (1982a), indicating
that automatic detection and controlled search could be carried out together, was given in Figure 11.16. The place where the joint performance matches the performance in both single task controls is called the independence point. This point was almost reached in the Schneider and Pisk (1982a) study.

The AOC provides a summary description of the way in which resources are shared between two tasks. In Figure 11.18b, as one moves along the AOC from upper left to lower right, one is tracing the progressive withdrawal of resources from the task plotted on the vertical axis, and the addition of those resources to the task plotted on the horizontal axis. If there are no concurrence costs, then the single task control conditions, which are plotted on the margins, will meet the extensions of the AOC interior curve. The single task control points in this case are indicated in the figure by a and b. If there are costs to managing two tasks together, and these costs are independent of the relative sharing of resources, then the single task control points on the margins will be superior to the extensions of the AOC function. This is indicated by the points c and d in the figure. Finally, if the concurrence costs depend on the degree of sharing, it may be difficult to tell whether this is the case from the AOC function. For example, suppose that concurrence costs are largest when each task is given equal resources, but drop to zero when the resources devoted to one of the tasks drops to zero. Then the AOC function will meet the single task control points, but will be depressed in the central region relative to the theoretical case where there are no concurrence costs.

It should be noted that subjects generally have a variety of strategies that can be adopted in dual task situations. It is possible to share resources in the usual sense, doing some of each task on a given trial (possibly even simultaneously), but is also possible to use a mixture strategy. The simplest mixture strategy would involve devoting all resources to just one task on a given trial, but varying over trials the particular task that is given those resources. If the performance on the margins is graphed in linear fashion, then such a mixture strategy will produce a point somewhere on the straight line connecting the two control points on the margin. "True" sharing could produce an AOC that lies outside this line, inside this line, or crossing this line, depending on the nature of the (unknown) PRFs and the nature of concurrence costs.

It is generally the case that the performance on the joint task can be compared to performance on another (or performance can be compared between different subjects, or conditions) by examining the AOCs. When the AOC lies entirely outside another, it is safe to conclude that joint performance is better. Furthermore, if the single task controls are identical in two cases, but one AOC curve is bowed more than another, and therefore lies outside, it can be considered that sharing is more efficient for the dominating AOC.

Two points are important to note. (1) It is generally useless to compare two situations if only one point on each of two AOCs is available. This is illustrated in Figure 11.19, Panels a, b, and c. Panels b and c show that either of the points in Panel a could lie on an AOC that is dominant. (2) Although an AOC is useful in many respects, it is basically a descriptive device, and provides relatively little information about the underlying mechanisms that are operating in the two tasks. For this reason, it is generally desirable to construct performance models for each task and their combination. The use of models may be possible to make inferences about concurrence costs, mixing of strategies, the effects of decision factors, the nature of the mechanisms underlying performance, and other matters. (In this respect and others, an analogy can be drawn between AOCs and the receiver operating characteristic of signal detection theory.) Examples of the use of models in conjunction with AOCs can be found in Kinchla (1980) and Sperring (1984). Discussions of inferences that can and cannot be drawn without models is found in Navon and Gopher (1979) and Navon (1984).

Sharing of Attention

An example of the use of AOCs to assess the sharing of attention in the domain of visual search comes from Sperring and Melchner (1978b). Subjects were asked to search a series of visual frames presented for 250 msec each. Each frame consisted of an outer region of large letters, and an interior region that in different conditions contained (a) small letters, (b) large but degraded letters, and (c) large numbers. One frame in the sequence contained two targets to be reported, one in the outer region, one in the inner region. The outer target was a randomly chosen digit, the inner target was a randomly chosen digit in conditions (a) and (b) but a randomly chosen letter in condition (c). See Figure 11.20, top, for illustrations (from Sperring & Melchner, 1978a). The subjects attempted to report both the inner and outer targets; in each condition three different attention allocation instructions were used: 50 percent to outer; 50 percent to outer; 10 percent to outer. Control conditions required report of just the outer, or inner, target.

The results for one subject are given in Figure 11.20. The condition in which attention...
sharing is easiest is (b), since the AOC is closest to the independence point (at the corner of the square); the hardest condition by this criterion is (c), in which letters and numbers are both to be detected.

These findings may be related to the search results discussed earlier. Training in conditions (a) and (b) was consistent in the sense that the subjective conditions may have been at least partially automatized. It is unlikely that automatization was operating fully, since the frame presentations were so rapid that even one task was producing only 70 percent correct responses. A data limitation was unlikely since replacement of distractors with dots led to perfect performance. On the other hand, serial search at a mean rate of 40 msec per comparison is also unlikely since load in each frame was 8 (number of digits in memory set) x 20 (display size) = 160. Performance could not have been as high as 70 percent if anything close to 180 normal comparisons were needed on each 250 msec frame. Very possibly the digits were automatically being treated as a single category, reducing the load to the display size of 20. However, a very rapid, partattentive search from the results of Schneider and Shiffrin (1977) that are shown in Figure 11.12 suggests that even a load of 20 may have made performance as high as 70 percent unlikely, were a serial comparison process operating. Probably the best guess is that in tasks (a) and (b) occasional automatic detection may have been used in parallel with a serial comparison on the digit category. Occasional automatic detection would have pushed performance toward the independence point, away from the diagonal, as was observed.

In the case of task (c), inconsistent responses probably ruled out the use or operation of automatic detection. In this case, serial comparisons were probably utilized (albeit with digits and possibly letters treated as one category) and something very close to a pure trading of performance between tasks should have occurred, as was observed. (Better performance than pure trading would be predicted because on frames where, say, the "outer" search was completed

early, the extra time would be wasted in the single task control, but could be used for "inner" search in the dual task.)

Although this general model may provide a plausible explanation, additional hypotheses are needed to explain why condition (b) should be superior to (a). A contingency analysis helps to clarify matters somewhat. Contingency analyses are used to assess the use of strategy mixtures. The idea is simple: If on a given trial only outer search, or only inner search, is carried out (called a switching model), then the subject should often detect one or the other target, but seldom both. On the other hand, if sharing occurs within a trial (whether simultaneously or successively, called a sharing model) then one might expect something like independence: The product of the marginal probabilities of detecting targets separately might equal the joint probability of detecting both. Sperling and Melchner's contingency data in (a) and (c) were more consistent with a switching model, and a pure sharing model could be ruled out. However, the data were not powerful enough to rule out either model for condition (b). Perhaps there was a time cost associated with switching from large to small characters, or from one category to another, that did not appear in switching from large characters to degraded large characters, so that within-trial sharing was effective only in condition (b). Other explanations are possible (perhaps related to differences in efficiency of automatic detection between (a) and (b)), but further discussion would be highly speculative.

### Compound vs. Concurrent Tasks

Sperling (1960) calls attention to an important distinction that has appeared in many guises in the literature. He classifies joint task studies as either concurrent or compound. Concurrent tasks are basically separate, have their own stimuli and responses, and do not have to interact other than through competition for attentional resources. Thus an "ideal subject" not subject to resource limitations would operate at the independence point (each joint task equal to its single task control). The "outer" and "inner" tasks assumed by Sperling in the preceding section provides an example of concurrent tasks. On the other hand, compound tasks are inherently interactive. What is presented on one task affects performance on the other, even for an "ideal subject" not subject to resource limitations. The interaction usually is caused by decision factors. For example, a single response might be required, based on the inputs to both tasks.

Suppose the Sperling and Melchner task were altered so that on each trial the subject was given two potential target stimuli, one from the display, and one not from the display, and asked to choose which had been presented. On joint trials the outer or inner target would be chosen randomly for testing; on single task trials, only a target from the relevant region would be tested. One might think that in the absence of attentive limitations, control performance would be equal to that on the subset of tests of that same region from the joint condition. This would be incorrect in the cases where the outer and inner targets are both numbers. In a joint test, choosing between, say, a 5 (target from outside) and a 5 (not in the display) would require consideration of stimuli everywhere in the display, not just in the outer region. Occasionally a 5 could be seen mistakenly in the inner region (i.e., a data limitation) reducing the probability of a correct choice. This could not happen in the control condition because only the outer region would be considered; a 5 seen in the inner region would be ignored. Thus the extra locations to be considered in the joint task would lower joint performance relative to the control conditions, even in the absence of attention limitations, and the independence point would not be reached. This would be an example of a compound task.

The allocation of resources determines which of several concurrent tasks are performed more or less well. In compound tasks, an additional factor must be considered: the effect of decision uncertainty. Thus in compound tasks an attentional allocation must be viewed first as a decision manipulation (as in signal detection or decision theory). Only after decision factors are properly taken into account can inferences concerning resources be made. Of course, when no loss due to sharing is observed, inferences are easy, but such an outcome is atypical. Further, while process models are very helpful for understanding the mechanisms at work in concurrent tasks, the resource allocation (i.e., the splitting mechanisms operating in compound tasks). If a trading membership in the AOC is observed for concurrent tasks then some sort of resource sharing seems likely (even if the resources are uninteresting such as "left arm movements"). On the other hand, an apparent trading relationship can appear in compound tasks purely on the basis of decision factors, even if no resource sharing is required (see Knoblauch, 1980). Sperling (1984) provides a useful analysis of this issue and many related ones.

The importance of taking decision factors into account has been noted by a variety of researchers. Eriksen and Spencer (1969) and Shiffrin and Gardner (1972) varied the number of simultaneous stimuli presented, thereby changing the decision components as display size changed. In an effort to control this problem, they used another condition in which the same stimuli were presented successively, rather than simultaneously (these results are discussed in a later section). In attention studies concerned with threshold stimuli, models incorporating decision theory are the norm (although perhaps the application have not always been correct—see Swets, 1984; Sperling, 1964). To the reader unfamiliar with signal detection methodology and models of decision factors in attention studies, the present discussion of compound and concurrent tasks must appear quite esoteric. Nonetheless, the distinctions are of crucial importance both in designing interpretable studies and in analyzing the data. There are many examples in the literature of conclusions whose validity cannot be assessed because decision factors vary across conditions, but are not properly taken into account by the authors.

### Focusing of Attention

On what can attention be focused, and how successful can the focusing be? Consider: tasks in which attention is to be directed toward some type of stimuli, and all others are to be strictly ignored. Probably the best examples of focusing involve signal location or signal modality. We shall see that signals occupying a given location in visual (or auditory) field (i.e., signal modality) can be given priority in processing, and signals in reasonably distant locations (or other modalities) can be ignored. We shall adopt the terminology of a region of focus to refer to all the time the focal attention is attended, even when location is not involved.

There are several plausible ways to assess the degree of successful focusing. First, performance in a region should rise as focusing on that
region increases, and fall as focusing decreases. Second, it might be required that signals in a region of maximum focus should be processed as well when there are signals outside this region as when there are not. This criterion should hold if the signals outside the region of focus do not interfere automatically (as they do when they attract attention automatically—see Figure 11.15—or as they do when they produce responses antagonistic to the responses required for signals in the region of focus—see the discussion of the Stroop effect on pages 765–766). Third, it might be required that the signals outside the region of focus should not be processed at all beyond the degree accomplished automatically. Other possible criteria involve effects upon automatic processing. The focusing upon one region might (a) increase the degree of automatic processing of signals in that region and/or (b) decrease the degree of depth of processing of signals outside that region.

Before turning to the data, it should be kept in mind that other criteria might be appropriate for attention tasks not requiring strict focusing. For such tasks, immediate availability to both regions is to be given primarily to one region (e.g., one ear in a shadowing task) but signals are nonetheless to be detected both in and out of the region of focus (e.g., in both ears). In such tasks there is obviously an inducement to attend to both regions, so that processing of signals not in the primary region of focus would be expected to increase, perhaps due to some slippage of attention to the other regions.

**Focusing upon Location**

In search tasks, focusing upon location is fairly successful. For example, Shiffrin and Schneider (1977) had subjects search a series of four-item square displays for targets in a varying mapping paradigm. When attention was focused on a specific diagonal of each four-character frame, detection probability was identical to the case when the frame size was two (two stimuli and two masks) randomly positioned in the four positions of each frame or two stimuli on the relevant diagonal. On the other hand, when the probable target was on the irrelevant diagonal, the probabilities of a target were varied across the eight positions in such a way that highly likely locations were opposite on the circle, and in general, the likelihoods varied considerably along the circumference of the circle. Performance varied across locations in a manner matching the probabilities of presentation. Shaw and Shaw (1977) proposed a model in which a limited total attentional capacity was distributed across locations in such a way as to maximize performance, and this model fit the data quite well. It is tempting to conclude that attention is simultaneously allocatable to disparate locations, but Shaw and Shaw were careful to point out that the basis for the attentional allocations was not ascertainable from the data. For example, subjects could have attended to different locations with different probabilities across trials. We shall return to this issue in the next section.

Results analogous to those in vision also obtain for auditory inputs. Whether location is defined by actual physical location or, more often, by nature or input, focusing is usually quite effective (e.g., Cherry, 1953; Cherry & Taylor, 1954; Poulton, 1953; Speth, Curtis, & Webster, 1954). This information in the region of focus is processed about as well with or without information present in other regions. On the other hand, information in nonattended locations is a certain amount of analysis. It is not clear how much of this analysis is generated by automatic mechanisms, and how much is due to a wandering or subsidiary allotment of attention. This issue will be dealt with shortly.

**Attentional Spots**

Posner, Snyder, and Davidson (1980) were able to disentangle the hypothesis of a distributed spatial attention from a moving focus of attention. The subject responded as quickly as possible to the presence of a simple above-threshold stimulus. The probability that the stimulus was presented in a location was varied experimentally across several locations, in a manner known to the subject. The responses were faster to more probable locations. In the condition relevant to the Shaw and Shaw (1977) study, two locations were designated: a most probable and a second most probable. When these two locations were adjacent, both were about equal and much faster than unlikely locations. When these two locations were separated, the second most likely location was about as slow as unlikely locations. These results suggested a "spotlight" model of visual-spatial attentional focus: Attention can be placed more or less at will in the visual field, but only in a contiguous spatial region (the "spotlight") at any given time. According to this hypothesis, enhanced performance in nonadjacent likely locations would be due to factors such as (1) mixing of attention focus across trials (e.g., Shaw and Shaw, 1977) or (2) movement of the attention focus from one location to another within a trial (e.g., in a search task serial comparisons along a diagonal of a display). Shiffrin and Schneider (1977).

This "spotlight" view has achieved some support and some extensions. For example, Läberg (1989) has subjects categorize five-letter words or categorize the central letter of a five-letter word or a five-letter monosyllable. This manipulation was used to focus attention by having the subject "concentrate" on a word as a whole (condition a), or sharpen on the central letter (condition b). Attentive focusing was assessed with a probe task: To digit 7 occasionally appeared instead of a word at what would have been word onset, in one of the five-letter positions, and required a speed response. In the other condition, the word did not appear, and was followed 500 msec later by the probe digit. The results are shown in Figure 11.2. Recognition performance in nonattended locations is a certain amount of analysis. It is not clear how much of this analysis is generated by automatic mechanisms, and how much is due to a wandering or subsidiary allotment of attention. This issue will be dealt with shortly.

**SELECTIVE ATTENTION**

In a subsequent study, LaBerge and Brown (1980) had subjects focus attention narrow or at a fixation point and then collected reaction times for an identification response to a sound object presented somewhere along a horizontal range of distances from fixation. As in Figure 11.1 experimental conditions were presented in the same order. Subjects were told in advance the extent of the range that applied on that trial, and this extent was varied widely. The results showed that slopes of the V shape were lower, the wider the range. If anything, faster for wider ranges, one assumes a gradient theory for a spotlight...
One possibility is that attention was focused on one size (or the other) and needed to be switched to the other size (see below), costing time that need not be spent for same size letters.

Many of the recent studies utilize a paradigm in which a large character or stimulus is made up in outline form of many smaller characters or stimuli. The subject could be asked to respond on the basis of the large character, the small characters, or both, and the responses to the two sizes could be compatible, incompatible, or neutral with respect to each other.

Navon (1977) found that when large letters are to be decided about, the small letters of which it is made up are effectively ignored. However, when small letters were to be focused upon for the decision, stoplight-like effects were caused by the large letters. When the identities of large and small letters matched, their responses were faster than when they mismatched (and indicated incompatible responses). Navon (1977) suggested a principle of global precedence, according to which information at the global level is invariably available prior to information at the local level.

Many researchers noted that perceptual factors were uncontrolled in such a study. Experiments were carried out to show that (1) large letters covering more than about 8-10 degrees of visual angle caused the global precedence effect to reverse, suggesting that speed of processing of either level was determined by ease of perceptual processing (Klimchuk & Wolf, 1978). (2) Distortions of the large letters to lower perceptibility led to local precedence, while distortion of small letters led to global precedence (Hoffman, 1980). Hoffman’s data suggests that subjects focused upon one level (global or local), searched it and if no target was found switched to the other level and searched it. Automatic processing of the unattended level occurred in parallel with this serial terminating process and produced facilitation or inhibition if perceptibility allowed it to take place quickly enough (3). If the local elements were fewer in number and somewhat larger than in Navon’s study, local precedence occurred (Martin, 1979). (4) Focusing initial attention upon a given level (local or global) had at least as large an effect upon the direction of precedence as perceptibility factors (attention tended to be given to the level that was relevant for the preceding trial; Ward, 1982). (5) Under conditions that produce global precedence, an analysis of the response time distributions rules out a strict precedence model in which global precedence precedes local analysis. The data were consistent with parallel extraction of information from both levels, with speed determined by perceptibility (Miller 1981).

There is perhaps evidence for some advantage of the global level in certain cases when perceptibility is better controlled (e.g., Navon & Norman, 1983; Hughes, Layton, Baird, & Lester, 1984), but other studies controlling perceptibility show either local precedence or no precedence at all (e.g., Pomerantz & Sager, 1975; Pomerantz 1983). Thus the studies to date do not suggest any inherent precedence of processing of a feature of a particular size or globality. In general, both levels are processed in parallel at rate determined by experimental conditions of presentation. The data do show a strong effect of attention focusing upon a given level of size or globality. The result of focusing may have several effects, including (1) causing a search order in line with the focus; (2) possibly improving perceptibility at the focused level; and (3) causing focusing on the next trial in accord with the level of the preceding trial. At the same time automatic processing of the unattended level occurs and can facilitate or inhibit responding depending on the compatibility of the response assignments. Presumably the automatic effects are akin to the Stroop effects seen in other settings.

**Inhibition of Objects in Nonfocused Regions**

It may be that objects presented in regions of nonfocus will be processed automatically and hence will generate encodings that must be in habit to carry out the requirements of the main task. Tipper (1980) and Tipper and Creasant (1985) presented two objects, each a different color. The object of a given color was to be reported. A second later a test might require report to the object previously ignored. With this subsequent test also involved color selection, responses were allowed to the ignored object (and allowed to an associate of the ignored object). In these circumstances, objects in regions of nonfocus are not treated purely passively solely through removal of attentive resources. Apparently the automatic responses that these objects produce require inhibition.
Attention Switching Time

Given that attentive resources tend to be applied serially, it is important to determine how quickly the focus of attention can shift. As we shall see, an upper limit of about 500 msec (or less) can be set with some confidence. Many different estimates have been obtained, depending on the type of attentional shift being studied.

Perhaps the simplest attention shift is one requiring movement of attention across the visual field (in the absence of eye movements; of course, attention shifts indexed by eye movements are limited by muscular constraints). Shalman, Remington, and McLean (1970) had subjects shift attention from a central cue to a peripheral target. Stimuli located at a point along the path between these two points received maximal facilitation at a time prior to maximal facilitation at the target. Such a result suggests a gradual movement of a limited region of maximum attention along a path from fixation to target. Tsai (1985) extended these results. Subjects fixated centrally and then received a brief dot in the periphery near the position where a target letter (O or X) would appear. The dot was designed to attract attention. After a delay that was experimentally varied, the target letter was presented for vocalization. Dots (and hence targets) were presented 4, 8, and 12 degrees to right and left of fixation. The results are shown in Figure 11.22. The farther is the target position from fixation, the greater is the SOA at which the curves reach asymptote. Various calculations on these data and the results of several control conditions suggested that when summoned by a cue in the periphery, attention moves toward the cue at a constant velocity of 1 degree per 8 msec. Further analyses suggested that the time to decide to move and to initiate the movement was 50 msec. In this case, total attention switching time obviously depends on "distance" to be moved (see also Erikson & Hoffman, 1972; Posner, 1980). It should be noted that this model of continuous and regular movement of attention focus is consistent with the data, but models in which movement is probabilistic and discrete cannot be ruled out. It should be pointed out that the various results on moving attentional spotlights are rather preliminary and fraught with interpretational difficulties, as discussed by Eriksen and Murphy (1987).

A somewhat different approach to the switching of visual attention was taken by Sperling and Reeves (1980). Two streams of characters were presented, one to the right and one to the left of fixation. On one side digits occurred sequentially at a rapid rate (e.g., 196 msec each); on the other side letters occurred somewhat less rapidly (e.g., 218 msec each). The subjects carried out a search task among the letters for the appearance of a critical target letter. Mapping was consistent and amount of training was sufficient that search was probably automatic. In any event targets were seldom missed. Upon detection of a target, the subject attempted to switch attention to the digits and report the "next" four digits starting with the one appearing simultaneously with the target. The results suggested that a "window" of digit attention opened about 400 msec after target detection. The 400 msec estimate of switching time includes any time to detect the target letter, overcome any automatic tendency there may have developed to attend to the target, switch to the digit locations and open the "gate".

Wachsmuth and Sperling (in press) used a variant of this paradigm in which only a string of successive digits was presented. The cue to respond with the next four digits was an outline square around one digit, or a brightening of one digit. In this case responses were clearly bimodal. The cue numeral was always reported (and occasionally the following numeral); there was then a gap and the remaining numerals reported are from a temporal region about 400 msec after the cue. The authors proposed that the initially reported numerals represent an automatic detection process, and the subsequent ones a controlled process of attention switching (this distinction being supported by demonstrations that these two regions of report could be separately manipulated by appropriate feedback). The similarity of the controlled attention shift data to those of Sperling and Reeves (1980) suggests that the requirement to move attention spatially in the earlier study was much less important than the time needed to open a window of attention temporarily.

It is interesting to contrast these results with those discussed on pages 760-761. In that case attention was to be focused continuously on one diagonal of a four item display. An "automatic" distractor on the irrelevant diagonal pulled attention away briefly (and automatically), but it apparently moved away and "snapped back" within no more than 200 msec. It seems natural that attention switching would be much faster in those circumstances. The movement of attention away may have been automatic, and attention may have been "pulled back" by a force that stayed in operation throughout the trial, since attention was supposed to have been fixed at all times on the relevant diagonal.

Visual search results provide other means of assessing attention switching. The cases in which serial terminating search is indicated by the means and variances of reaction times (i.e., varied mapping tasks) suggest an interpretation in terms of attention switching. If so, both the switching and the comparison together must take an average of 40 msec. Of course, visual attention need be switched only a small distance since the displays fall within several degrees of fixation. It is less clear whether or not far attention must be switched among memory set items. For both types of search, the sequence of switches could be "preplanned" (although the subject may be unaware of the planning).

If we move from the visual modality, yet other methods are used to estimate switching times. The original studies on switching of auditory attention between ears were carried out by Broadbent (1958). In one type of study, six auditory digits are presented to the subject in three groups of two, each simultaneous pair consisting of a digit to one ear and another digit to the other ear. The rate of presentation of these pairs was varied. At two pairs per second, subjects asked to report the digits report them most often first from one ear and then the other. If it is very difficult to report the digits in order of presentation, pair by pair. When presentation rate was slowed down to one pair each two seconds, then report in temporal order could be carried out as well as in order of location. Broadbent (1958) found that attention could not be switched well between ears at fast rates, but could be switched at 2 seconds per pair; thus two shifts of attention and two perceptions of digits could occur in 1 to 2 seconds. Subtracting about one half second for perception gives 1 1/2 to 2 seconds as a rough estimate of switching time.

A large number of studies in subsequent years was aimed at the validity of Broadbent's
conclusion from this paradigm (for one summary, see Broadbent, 1971). One main line of attack involved studies utilizing items of different types (e.g., digits and letters, words forming meaningful phrases and digits, etc.). If digits and letters, for example, alternate between ears then there is at least a strong tendency to report by item type as by ear. Yntema and Trask (1963) suggested that information is tagged during storage and the tags later enable selection of items during retrieval. Broadbent and Gregory (1964) showed that at fast rates, report of items by alternating type is more difficult than by same type (e.g., A64L9 harder than A164J9, even when all items are presented to one ear. They concluded that a second type of selection was occurring in these situations, selection by type, rather than by ear (whether type selection is "early" or at retrieval, and how much time is needed for switching such selection, is unclear).

We shall not attempt to discuss in this chapter the extensive series of studies on the topic of attention. To extend that attention can be focused in auditory situations, attentional focus can be switched and the switch takes some time. No very precise estimates of switching times seem to be available, but at least one type of switching between ears may take from 1/6 to 1/2 second.

Bottlenecks of Attention

As we have seen, attention cannot be divided easily. Why is this the case? Broadbent (1957, 1958) proposed a filter theory, based on the results of auditory detection and shadowing studies. There were three stages to the theory: (1) a short-term system; (2) a selective filter; (3) a limited capacity processing channel. The short-term system contains all information in parallel, and stores it briefly. This system is similar to that described as pre-attentive by other authors and the processing is what we have termed automatic. Most of the examples utilized by Broadbent suggested that this system is restricted to analysis of primitive physical features, but it is not clear whether such a restriction is a necessary part of the theory.

The second phase of the system was a rather strict filter that allows only those stimuli on a designated "channel" to pass through for further processing. What a channel is has never been entirely clear, but probably corresponds to those attributes and features that lead to effective focusing of attention, such as those discussed in the section on focusing. Attributes based on simple physical features define a channel in most applications (e.g., location, color) and stimuli varying that attribute are allowed to pass the filter.

There are two characteristics of such a model that have led to a great deal of research: (1) Is the filter completely selective, or does it allow information to be passed on unattended channels? (2) Whatever the nature of the filter, how deep in the processing system is it placed?

The initial position by Broadbent stipulated a completely selective filter, with no passage of information on other channels. It soon became clear that this simple view needed modification. In many studies by Treisman and others (e.g., Treisman, 1969 for a summary) it became clear that various types of information about stimuli on unattended channels were sometimes available to subjects. Many of the initial studies utilized auditory stimuli, for example, reporting by aloud a message in one ear while detecting occasional signals presented to either ear (e.g., Treisman & Riley, 1969). The results are clear. Signals are better detected on the attended ear, but are also detected to some degree on the unattended ear. Such results led Treisman (1960) to modify the filter model, to allow the possibility of less than complete selectivity. The attention model posited that the attended channel would receive "complete" processing but the other channels would receive an attenuated degree of processing.

There are many conceivable variants of attention models. The particular model proposed by Treisman (1960) supposed detection occurs when "dictionary" units are activated beyond threshold. The items in the attended channel are transmitted "normally," but all stimuli on the unattended channel have their transmission efficiency reduced. The "signal-to-noise" ratio is reduced, and the threshold is presumably raised concurrently. In our present terminology, Treisman's (1960) attentional mechanism acts by reducing the effectiveness of automatic processing on unattended channels. Because certain thresholds on unattended channels can be much higher than others (either permanently or temporarily), the model can explain why "unattended" items such as the subject's own name are sometimes detected (e.g., Moray, 1959), or why semantic relatedness effects take place (e.g., while shadowing one ear, subjects follow connected discourse to the other ear for a word or two when a switch occurs). Thresholds vary on both attended and unattended channels for individual stimuli for a variety of reasons: long-term importance (e.g., prior learning), contextual priming (e.g., spreading activation from recent related inputs), and expectancy (in our terminology, negative mechanisms).

This model seems reasonable, but one interesting possibility should be noted. If automatic detection is accepted as a mechanism, then it may be possible to salvage the original form of filter theory. A certain amount of processing and detection may occur automatically regardless of the channel attended. This automatic detection could account for detection of "unattended" stimuli, and could be similar in character to the notion of a dictionary unit exceeding threshold. The advantage of the original form of the model would derive from a different source: an attentive mechanism such as a serial comparison process. If this approach is taken, it leads to a certain reinterpretation of the data, and it may even be possible for filter theory to be resurrected (as long as the filter refers to the non-automatic part of the processing system). Whether the resultant filter theory would in fact be much different in substance from Treisman's attention theory is a debatable point.

To reassess filter theory it helps to distinguish weak and strong versions of the model. The strong version postulates that the filter can be set to a channel and remain there until a conscious decision to switch is made. Shiffrin and Schneider (1977) carried out a relevant study. Subjects were instructed to attend to one diagonal of a four item square display in a multiple frame, varied-mapping search task. Although distractor items on the irrelevant diagonal had no effect, target items on the irrelevant diagonal (which should have been ignored) were sometimes processed and hindered processing on the relevant diagonal. These targets were the same items that were given varied training, and hence were unlikely to have attracted attention automatically. Thus a strong version of filter theory is difficult to sustain.

The weak version of filter theory posits that the filter is all-or-none at any moment, but occasionally wanders from the channel of focus, either accidentally or by intent of the subject. Distinguishing such a model from an attention model would at least be extremely difficult.

The problem in most general terms is one of distinguishing two approaches in cases where attention is apparently being shared: (1) Attention is given in some measure to several sources at once (a type of attention theory). (2) Attention is given to one source at one time, but is switched either within a trial or between trials. The switching model is discussed in the section on sharing. In general, subtle techniques are needed to disentangle these models. If switching occurs only between trials then contingency analyses may help provide a check of the model's validity, otherwise the application of quantitative models to the data would probably be needed (See the discussions on pages 775-781, and discussions by Kinchla, 1980 and Ebling, 1986).

In 1965 Treisman modified her version of attention theory, partly to account for cases in which aspects of messages on an unattended channel are invariably noticed. For example, major changes of attributes on simple basis, positions are easy to note (Lawson, 1966, Treisman & Ridley, 1968). The new theory proposed a hierarchy of analyzers operating in parallel. Several analyzers operate on a "single" input in parallel, explaining such effects as the stroop effect (e.g., outputs of color analyzers may compete with the outputs of some sort of "reading" analyzer). Two or more inputs can be handled in parallel, but only if they don't contact the same analyzers. Any one analyzer must handle inputs serially. Such an account can explain a result such as that of Rollins and Hendrickx (1950) who showed that auditory shadowing and visual search would operate together some of the time independently, but shadowing and rhyme judgments for visual inputs could not be handled in parallel.

The multiple analyzer approach is consistent with the notion of the data concerning automatic processing. On the other hand, the notion that different inputs requiring one analyst must be treated serially is very likely wrong. We have seen in numerous examples from memory search and visual search studies that automatic processes can occur in parallel at virtually any depth of analysis, from peripheral to central, given consistent training. For example, numerous words and digits can be processed in parallel.
parallel up to the level of category knowledge (Schneider and Fisk, 1984), even though various analyzers such as shape and modality (visual) must be utilized numerous times. Nonetheless, it should be noted that the idea of multiple analyzers went a good way toward a theory of automatic processes, even though the Treisman (1969) version seems to have stopped a bit short of the views suggested in this chapter.

The Treisman (1968) approach in effect introduced multiple bottlenecks or filters in the processing of one. A related hypothesis holds that there are multiple resource pools rather than a single unitary central resource. This issue will be taken up in a later section.

**Depth of the Attentional Bottleneck**

Perhaps more than any other issue in the study of attention, research and controversy have been associated with a single question: the placement in the processing system of the attentional bottleneck(s). The approaches of Broadbent (1957, 1969) and Treisman (1969, 1964, 1969) seemed to suggest a relatively peripheral placement, shortly after certain physical attributes have been extracted automatically (presumably, or and Treisman's) views have been largely proposed quite different models. A somewhat free interpretation of their views goes as follows: All processing occurs automatically until the results are placed in short-term memory; the bottlenecks of attention then become the limitations of short-term memory (see also Shiffrin, 1976). One way these views were contrasted concerned the issue of depth or degree of processing of "unattended" inputs. As we have seen, even when unattended inputs are apparently having no effect on behavior, other types of tests usually show that many of those same inputs had been analyzed to at least the level of meaning (e.g., category membership; see page 771). Of course, such analysis is most likely to be automatic, but many of the studies in this area have been carried out without much thought to the possible role of automatization.

In this chapter it is possible only to touch upon some of the different approaches to this issue. Consider two visual search studies by Francolinci and Egeth (1979, 1980). In both studies, subjects viewed letters and/or digits randomly positioned around the circumference of an imaginary circle. In the 1979 study, red and black letters were presented; subjects searched for a target letter and were told that if one was present, it would be red. In this case, reaction time increased not only with the number of relevant red, correct, but also with the number of irrelevant, black, letters. On the other hand, when subjects were asked to count the number of red letters present, the number of irrelevant black letters had no effect. Francolinci and Egeth (1979) concluded that an early selectivity based on color (process red items, but not black) occurred in the counting task, but not the detection task. In one sense of the term "selectivity" this conclusion is certainly correct, but it should not be concluded that the "unattended" black items did not have their names processed automatically in the counting task.

It would be more parsimonious to assume that in both these tasks the automatic processing system provided "character name" information, but that this information was not involved in counting the task. Also, the counting is much slower than detecting so a fast process (perhaps even serial in nature) could be locating red items for a much slower counting system to process. On the other hand, detecting operates very quickly, so that there is a tendency to check all items, regardless of color. A similar analysis is proposed by Green & Anderson (1956, and Smith, 1969). These studies used detection of two digit numbers, producing slower comparisons, and hence greater benefits of selectivity by color. Also Egeth, Vrils, & Garbamp, 1984, showed that digits do occur in a harder detection task involving search for conjunctions of features—see page 790). A related finding by Dauinas (Shiffrin, Dauinas, & Schneider, 1981) showed subjects could not selectively count the numbers in a display of numbers and letters. However, if the subjects had been consistently trained to detect automatically number targets in letter distractors, then when transferred to the counting task, selection on the basis of character type (number vs. letter) became possible.

Francolinci and Egeth (1980) utilized the Stroop effect in a task requiring counting of the red characters and not the black. Either the red items or the black consisted of digits different from the required counting response. The Stroop effect (interference with the counting response) occurred when the interfering digits were red, but not black. The authors concluded the irrelevant black items were not processed to the level of character name, since interference did not occur. However, we have seen that the Stroop effect is often dilated or eliminated when attention is directed to locations different from the focus of attention (e.g., Goolkasian, 1968; Kahneman and Henik, 1968). Thus the Francolinci and Egeth failure to obtain an interference effect does not imply that the black items were not given deeper processing. One way to settle this issue within this type of paradigm would involve showing that an item that does not produce a Stroop effect (due to attention focused elsewhere) nevertheless is processed to the level of meaning (perhaps using a method like that of Eich, 1984; see the section on memory effects).

Since deep processing has been shown to occur for unattended items in other paradigms, it seems likely that it occurs also in these paradigms involving the Stroop effect.

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require detailed mathematical models of processes underlying task performance (see Sterling, 1984; Sweet, 1984). A few examples help to clarify some of the problems. First, all conclusions must take into account performance levels that could be achieved by an "ideal detector" that has no attentional limitations to begin with. Most theories assume that degraded stimuli are "noisy." Targets and distractors will sometimes be perceived incorrectly and sometimes completely but incorrectly. In cases of incomplete processing, the features that are perceived are sometimes consistent and sometimes inconsistent with targets or distractors. Under these circumstances, correct decisions are inevitably more difficult when more distractors are presented. For example, the probability that some distractor will be misperceived as a target rises as the number of distractors rises. In order to control for decision effects of this kind, Eriksen and Spencer (1969), and Shiffrin and Gardner (1972), contrasted two basic conditions. In one, all the stimuli are presented together, in the other, all the stimuli are presented sequentially. The detection decision that is made at the end of either of these types of trials should involve similar decision factors since the presented stimuli are identical in both cases. An ideal detector would exhibit equal performance in these cases. On the other hand, most limitations should cause poorer processing when stimuli are simultaneous, since attention must be divided among multiple inputs when stimuli are presented successively at an equal or slowed rate, attention could be switched at each in turn.

Shiffrin and Gardner (1972) carried out seven variants of this paradigm. Four characters were presented at threshold. A trial contained three distractors and one of two possible targets. The subject attempted to determine which of the two targets was presented. In the simultaneous condition, all four stimuli occurred together for 1 msec each. In the successive condition, each stimulus followed upon the previous, each presented for 1 msec. In both conditions, mask patterns preceded and followed each stimulus to control the effective duration of the stimulus. Surprisingly, performance was, if anything, better in the simultaneous condition. This result was replicated in a long series of studies by Shiffrin and his colleagues (summarized in Shiffrin, 1975 and many other researchers. Studies varying in
between successive stimuli, modality of presentation, type of stimuli, and type of task.

Since the results showed no successive advantage, Shiffrin (1975a) concluded that there could be no corresponding bottleneck. This may be true, but left unexplained was the failure to find any attentional effect of dividing attention. These effects have been measured at all levels of the system. Prof. R. Massaro (1970) showed that the use of identical distractors may have provided an "oddity" cue to the target location, thereby eliminating the necessity for spreading attention to the distractor locations and for taking distractor information into account in the decision. When distractors are very dissimilar to targets, this hypothesis may be correct. When distractors are confusable with targets, it seems unlikely that any very discriminable cue "pointing" to the target location would be available under threshold conditions (also see Burns, 1979). Foyle (1981) collected evidence for another factor explaining the failure to find effects. Since all the successful studies had used a consistent mapping paradigm, automatic target detection may have developed, directing attention to the target location. Foyle repeated the Shiffrin and Garden (1972) task, but added a variable mapping condition; in this extra condition an advantage for discriminative presentation appeared. Foyle concluded that oddity alone could not account for the results since the oddity factor was present in both mapping conditions. Thus, either automatic detection or a combination of the factors of oddity and automatic detection probably accounts for the failure to find a divided attention deficit in the successive-simultaneous experiments.

The hypothesis that automatic detection can develop in threshold conditions is problematic. If threshold conditions produce "noisy" stimuli, then targets and distractors will be confused with each other on occasion, and the consistency of training will be reduced, if not eliminated. Thus only in very special conditions with limited confusion can one expect automatic detection to develop. Foyle (1981) found that increasing the confusion, the number of stimuli, or the diversity of distractors all produced a successive advantage even when "consistent" training was used. This result suggests that only in very limited conditions with low confusion can automatic detection be expected to develop in threshold tasks, and otherwise a successive advantage should be seen.

The implications of these various findings for early or late selection are somewhat different than was originally thought. If automatic detection is operating, then attentional bottlenecks become an orthogonal issue. The whole attentional system is, in effect, bypassed. On the other hand, when varied mapping is used, or when confusability is high, automatic detection does not operate effectively and the successive stimulus is better processed. As usual in such cases, the locus of the bottleneck is unclear. (1) Processing of features could be less efficient when more stimuli are present. (2) All features could be processed equally regardless of load and entered briefly into a very short-term memory, but forgotten more often before they can be utilized when presentation is simultaneous.

Finally, it should be noted that it is possible to assess threshold processing in tasks other than those using the successive-simultaneous technique. This could even be desirable since there is the possibility that more forgetting could occur in the successive condition by the time the decision is made. In these other tasks, it is essential to have a model for the decision processes at work. A good example comes from Kinnamon (1975) who showed that subjects can process two adjacent stimuli without perceptual limitations, once decision factors are taken into account.

The importance of utilizing decision models to analyze threshold tasks is illustrated by results such as those of Bashkani and Bacharach (1980). They demonstrated that a threshold signal was better processed in a location whose expectation of containing a signal was high (and worse processed in an unlikely location), a result similar to many others (see the focusing section). A recovery operations (ROC) was used to demonstrate this point. However, as is true for AOCs, an ROC curve is a summary measure that tells little of underlying mechanisms. In the case of the present study, the authors set out a compound task (see the section on dividing attention) in which both locations contribute to a single decision about target location. As demonstrated by Kinnamon, when several locations may contribute to a decision, ROC curves computed by standard methods can be moved inward or outward by decision factors, weighting schemes and biases, and thus tell us very little about the sources of a performance deficit.

It should be noted that even when an analysis carried out automatically took into account decision factors, or instead a concurrent task procedure utilized, and the results demonstrated that better information is obtained under threshold conditions from attended locations, such a finding would not have much bearing on the location of the attentional bottleneck. Believers in "late" limitations could argue that the information from all locations was processed and placed in short-term memory where attention began to operate upon it in an order determined by signal probability. Information that is lost with later in the decision sequence could be impoverished due to rapid forgetting of sensory features (especially in threshold tasks in which the sensory features may have been encoded in memory very weakly). Finally, as pointed out in the section on modifiability, automatic processes may sometimes be modifiable by allocation of attentional resources; if so, information transmission may be affected by the probability, say, of location, but this fact would not establish a mandatory early focus for an attentional bottleneck. Fortunately we shall assess the current situation on the target and the bottleneck.

Perceptual Set and Response Set

Broadbent's (1971) Kahneman (1973), and others have argued for a rather fundamental disconnection between what Broadbent (1971) has termed the stimulus set and response set (or alternatively filtering and pigeonholing). Broadbent viewed these as two fundamentally different selection processes that the subject could adopt as needed. Stimulus set refers to selection of certain items to pass the filter on the basis of some common characteristic possessed by the stimuli (usually a simple, physical, peripheral characteristic such as modality, location, color, etc.). Response set is the selection of certain classes of responses to output based on the available evidence, however strong. Thus attending to items on one ear (e.g. repeating them) is an example of stimulus set; attending to digits (e.g. repeating them) regardless of ear is an example of response set.

At first glance this distinction seems compelling and fundamental. For example, as Broadbent (1971) pointed out, response set produces no instructions from the wrong set. Subjects attempting to report items from one ear occlusively report items from the other, whereas subjects attempting to report digits do not report letters. Indeed, there is an important difference between the two report conditions; the tasks impose markedly different decision structures in the two cases. It would be quite misleading, however, to suggest that this argument implies anything about the differential nature of attending to locations vs. characteristics, category, or about the depth of attentional selection.

The easiest way to demonstrate this fact is through an example. One can change the task in such a way that the roles of characteristics and location are exactly reversed. Let the new task consist of the visual presentation of 20 characters, 10 to the right side of the visual field, and 10 to the left. On each side, 5 of the characters will be the digit "5," and 5 of the characters will be the letter "A." The instruction "report all letters" in the new task corresponds to the instruction "report names of all left ear items" in the original task. Intrusions of locations of 5s in the new task corresponds to intrusions of names of right ear items in the original task. Further, it would be possible to apply the traditional two-stage argument in both cases: One property is identified (letter, location of ear) and used to identify a subset of items to be analyzed further for other properties (location, nature of character). Similarly, the instruction "report all left field locations" in the new task corresponds to the instruction "report all digits" in the original task. In the new task no right locations will be reported, and in the original task, no letters will be reported. This example shows that there is a logically necessary relationship between response set and stimulus set and particular stimulus characteristics and/or depth of processing.

In practice, however, especially in auditory settings, tasks are usually designed so that stimuli occupy the basis of simple, physical, peripheral features such as location, and response set refers to selection on the basis of more central, derived, categorical features, such as "letter vs. digit." Thus in practice there is a strong correlation between the two kinds of attentional selection that proves possible. The correlation occurs because, in the absence of special training selection is far easier on the basis of simple physical features. Very likely, the persistence
the "stimulus set"—"response set" distinction lies in the fact that the task assignments have usually equated stimulus set with physical feature selection. Selection on the basis of more central, categorical features (which in the usual tasks is equated with "response set") is possible after consistent training produces automatic responses. These studies were reported earlier in the paper.

Selection on the basis of symbol name, or even category name (e.g., Schneider & Pisk, 1984) is not hard to demonstrate. One should not be misled, however, into thinking that these two situations, physical feature selection and trained feature selection, are identical. At least in the studies that have been carried out thus far, one set of items, or features, is trained to attract attention, while the remaining item(s) or feature(s) do not attract attention and may repel it. Thus the subject cannot shift the basis of selection once it has been established through training (see Figure 11.15). In the case of physical features such as location, effective selection can occur even if the feature (location) is shifted from one trial to the next. It is not yet known whether a different kind of training procedure (perhaps one that would produce an automatic attention response) would allow selection to occur on a trial-by-trial basis for "deeper" features. In any event, at the present time, it is clear that the simpler, more primitive, and more "physical" a feature is, the more effective it will be as a cue for selection (a conclusion reflecting those in the section on focused attention).

It can be concluded, then, that "early" selection on the basis of primitive physical features is indeed easier than "late" selection on the basis of learned, complex, features. This does not imply that there is an early attentional bottleneck; however; it implies, rather, that perceptual space divides up (or can be divided up through application of attention) into regions on the basis of simple, salient features (see the next section). Early selection and an early bottleneck are not equivalent concepts, because early selection does not prohibit very deep processing of items that are not selected, whereas an early bottleneck (in, say, the sense of Broadbent's filter theory) does not.

Assessment of Bottleneck Depth

The field of attention owes a good deal of its technical development to research aimed at determining the locus of the attentional bottleneck. However, if one accepts the view that a good deal of processing occurs automatically, that automatic processing is not restricted to any particular stage of the processing system, and that attention can be applied at most or all stages of processing, then there is no one stage at which a bottleneck appears. Instead, whatever information extraction is carried out by attentive processes rather than automatic ones is subject to limitations, and these limitations will appear at whatever processing stages are being improved by attention.

A geometric interpretation of these views might run as follows. The early theories tended to construe processing as consisting of automatic processing in parallel followed by limited attentive processing (see Figure 11.23, Panel A). The view suggested in the preceding paragraph would have both automatic and attentive processing operating side by side at each stage of processing, with the attentive resources limited (see Figure 11.23, Panel B). According to this view, in the typical task, most "early" processing tends to be automatic, and the least attentive processing occurs at early stages, while less "late" processing is automatic and more attentive processing occurs at late stages. In Panel B of the figure this concept is illustrated by the widths of the wedge shaped regions. The attentive wedge is smaller to indicate that attentive processing is limited in capacity or resources. (This view is similar in some ways to that proposed by Johnston & Heins, 1978, and related to the model of Schneider, 1986).

Features, Dimensions, and Objects

Throughout this chapter, we have used rather imprecise terminology when referring to stimuli, lumping together features, attributes, and dimensions rather loosely, and not attempting to draw any hard and fast line between simple, physical, or complex, features, and more derived features. Many researchers have attempted to draw these sorts of distinctions quite precisely and relate them to attentional phenomena. Some of the key ideas are treated in this section, but the discussion will be brief since this topic is covered elsewhere (e.g., see Treisman, in press) and detailed coverage would take us far afield into areas of perception and perceptual development. The discussion will be limited to visual stimuli, though similar issues and results occur for other types of stimuli.

Perceptual Organization

As a conceptual starting point, we might consider the process of perceptual organization. When a visual presentation occurs, a good deal of organization takes place, including segmentation into figure and ground, and a breakdown into objects. A good deal of this organization may take place automatically, based in part on detection of homogenous regions, graded changes, and discontinuities in the visual field, but there is ample evidence that these processes are affected strongly by attentive processes as well (e.g., see Neisser, 1967; Kubovy & Pomerantz, 1981; Spohr & Lehmkuhle, 1982). One of many examples comes from Kinebuchi (1980). Figure 11.24 illustrates the type of stimuli. A letter was presented as zeros in a background of Xs, or vice versa. Before each trial a three letter memory set was presented and the subject stated as quickly as possible whether one of these was present in the display. The probability of the letter being made of zeros was varied in different conditions. The results in Figure 11.24 gives the response latencies for letters in zeros graphed against the latency for letters in Xs. For each probability condition. The latencies show a trading relationship between the two types of figure-ground organization. Apparently the subjects choose an initial organization (i.e., "figure" in zeros or Xs) with probabilities determined by the likelihoods, respond quickly if the letter is in accord with

![Figure 11.23](image-url)

**Figure 11.23.** Two depictions of models of the interaction of automatic and attentive processes. (A) Traditional model in which automatic processes follow automatic ones. (B) Model in which automatic and attentive processes co-occur at all levels of processing.
that organization, but otherwise must switch organizations, and respond more slowly as a result. Apparently both organizations are not seen at once, so the initial organization is a crucial determinant of subsequent processing.

An example of organizational effects on attention in the search domain comes from Prinzmetal and Banks (1977). Subjects attempted to say as rapidly as possible whether displays contained a T or F. Distractors were non-letter stimuli similar to both T and F. The displays were constructed to be non-regular in their spatial distribution. For example, one type of display would have five items arranged linearly along a diagonal, with a single extra item off to one side. When the target was in the perceptually "odd" position, responses were faster than when on the diagonal. Similar results were obtained with other spatial configurations. Perhaps the perceptual organization of the displays takes place early and automatically and guides the search process. Either the smaller distinct regions call for attention automatically, or the subject directs attention to the smaller of the perceptually distinct regions; in either case the search would be faster if it tended to begin with the item in the "odd" position in the display. (Similar results were obtained by Brown & Monk, 1975, and Carter, 1982. Carter showed that perceptual grouping by color played the same role as grouping by spatial arrangement.)

Integrity, Separability, and Configurality

The organization of a visual presentation into separate objects, or into attributes of single objects, is an important determinant of processing. Although sometimes the organization is modifiable by attention, other times it seems to be immutable. Consider a case where two distinct objects are presented side by side. One might expect that these objects would be separable (Garner, 1974), so that one could be attended and the other ignored. This quite often turns out to be the case, and is in fact one of the defining characteristics of separable dimensions, even when the dimensions are part of what we would think of as a single object. An example from Garner and Feldolfy (1979) consisted of circles of two sizes contained in a radius pointing in one of two directions. Subjects sorted stimuli as rapidly as possible. In control sorts two stimuli are used, and the irrelevant dimension does not vary (e.g., two circles to be classified on the basis of different angles). In correlated sorts both dimensions are redundant in the two stimuli to be sorted (e.g., a large circle vs. a small circle with the other angle). In orthogonal sorts, all four stimuli are used, but classification is based on only one dimension; hence, there is variation on the irrelevant dimension (e.g., classify on the basis of angle, but all four stimuli appear). All three types of sorts take equal time for these stimuli, verifying that the dimensions are separable.

Other types of stimuli are made of integral dimensions because correlated tests lead to improved speed and orthogonal tests lead to reduced speed. Feldolfy (1974) showed this to be the case for rectangles made from two heights and two widths. In those cases perception of one characteristic of the stimulus is affected by the other, as if both had to be attended to some degree (at least both influenced the decision, so focusing was not completely successful).

Garner originally tried on logical grounds to divide stimulus dimensions into separable and integral pairs, but a number of findings have shown this to be difficult if not impossible (e.g., Garner, 1978; Pomerantz, 1983). One problem arose when Pomerantz and Garner (1973) used parenthetical pairs as stimuli: ((2, 0)), (0). The direction of the parenthesis is one dimension, and left or right location is the other. In this case redundancy probably got in the way, but orthogonality had a cost. Most important, (1 vs. 7) provided the fastest discrimination of any pair, while (2 vs. 0) was slowest. Thus the two redundant pairs were the fastest and slowest. These combinations of dimensions were called configurational because they seemed to produce performance dependent on emergent features that arose from the particular arrangement.

As cases began to accumulate that did not seem to be consistent with even this three way classification scheme (integral, separable, configurational), and as other classification tasks were added to those given above, more and more refined and complex classification schemes for stimulus arrangements began to be developed (e.g., Pomerantz, 1981, 1983; Garner, 1978). These will not be described here, because it seems clear that the process of determining the stimulus features that produce different sorts of attentional effects is still evolving rapidly. Furthermore, the classification schemes are becoming so complex that it is difficult to say a priori which stimuli will fall into which categories. Stimuli can be found which focusing, divid- ing, and combining are possible or impossible, but these stimuli do not map easily onto a "simplicity" scale (Garner, 1978).

The reader will no doubt notice that the features, dimensions, and attributes we have discussed are defined physically and are just one choice of many possible descriptions of stimuli. Thus height and width may be sufficient to describe any rectangle stimulus, but height and width do not have to be the psychological dimensions by which rectangles are seen. A plausible alternative might be shape (height to width ratio) and area (height times width). Such an alternative has empirical support (e.g., Weintraub, 1971).

Cheng and Pachella (1964) generalize this view and question whether integral psychological dimensions exist. The findings of gains due to correlated dimensional cues and losses due to variation of irrelevant, orthogonal, dimensional values, may be due to some choice of dimensions for analysis that does not correspond to the

Figure 11.24. From Kinchla (1980). (a) Illustrative stimulus patterns from the "figure ground" experiment, which can be seen as a large L or N with X defining the "figure" (S1) or Os defining the figure (S2). (b) Empirical and theoretical organizational operating characteristic (OCO) functions. From "The Measurement of Attention" by R.A. Kinchla in Attention and Performance VIII (p. 232), R.S. Nickerson (Ed.). 1980. Hillsdale, NJ: Erlbaum. Copyright 1980 by the International Association for the Study of Attention and Performance. Reprinted by permission.
underlying psychological dimensions. Cheng and Pachella used isocorces triangles as stimuli; the four stimuli vary in ways that can be described along different pairs of dimensions. The psychological dimensions were "shape" and something else that could be described as size, or height or width. The non-psychological dimensions were lengths of particular sides. For the psychological dimensions, separability was observed. Variation of the irrelevant dimension produced no cost. However, cost was observed for the non-psychological dimensions. Instead of concluding that these dimensions are integral, Cheng and Pachella suggest that they are not true dimensions at all. Furthermore, they raise the possibility that other problems with dimensional analysis (e.g., configurality, non-symmetric integrality) may be due to the choice of dimensions that do not correspond to psychological ones.

Although the Cheng and Pachella (1984) view is worthy of consideration, even psychologically separable dimensions such as color and size do not always produce data consistency with the view that they are independent. For example, Smith and Kemler Nelson (1984) show that color and size are dealt with in separable fashion when responses may be made relatively slowly, but are dealt with in apparently integral fashion when greatly speeded responses are required (in certain cases involving sufficiently young children). Such data certainly raise the possibility that a primitive integral analysis of stimuli tends to occur in addition to analysis along separable dimensions.

One way to think about such findings is to assume that prior learning as well as innate stimulus properties produce automatic perceptual encoding. This automatic encoding can be affected by attentive mechanisms in many cases, especially when the stimuli allow multiple interpretations. Nonetheless, automatic analysis proceeds at many levels in parallel and produces a perceptual organization. This organization then becomes a crucial determinant of the subsequent attentive processing that can take place.

This view is seen in models by Neisser (1976), Lockhead (1972), Monahan and Lockhead (1977) and others. It differs in some ways from another recent view of attentional processing suggested by Treisman and her colleagues, reviewed in the next section.

**Feature Integration**

The data mentioned in the preceding section concerning configurability, the Smith and (Kemler) Nelson data, and the (rather weak) data in the focusing section concerning the "global precedence" hypothesis suggest an initial stage of processing at a global level of analysis, followed by an analysis of parts, the second analysis being attentional driven. This view may be contrasted with the recent theories of Treisman and her colleagues (e.g., Treisman, Singh, & Gelade, 1977; Treisman & Gelade, 1980; Treisman, in press). The feature integration model assumes features come first in perception. Features are assumed to be registered automatically and in parallel, and to consist of values on primitive dimensions such as color, orientation, spatial frequency, brightness, and direction of movement. Objects, consisting of collections of features, are not encoded automatically and must be constructed by use of the "glue" of focal attention. Once attention is used to form objects, these objects enter (short-term) memory where they are stored and dealt with separately. For example, Smith and Kemler Nelson (1984) show that color and size are dealt with in separable fashion when responses may be made relatively slowly, but are dealt with in apparently integral fashion when greatly speeded responses are required (in certain cases involving sufficiently young children). Such data certainly raise the possibility that a primitive integral analysis of stimuli tends to occur in addition to analysis along separable dimensions.

In this simple form, the theory is quite incapable of explaining very much perception or behavior. For example, as Treisman and Gelade (1980) point out, we would expect the sun to remain a yellow sky, even if our attention is directed elsewhere. Thus our knowledge, learning, and experience must also act to conjoin features into objects. Presumably the top-down effects of prior knowledge occur automatically, but not in all cases.

The theory has been extended to the idea that conjoining features do not form a particular, well-learned combination. Under such circumstances, when attention is not focused upon groups of features, objects should not be formed in an automatic, preattentive manner, and features will be relatively free to recombine in illusory ways.

There are two types of feature pairs that need to be distinguished: separable and integral (the definitions of empirical tests do not correspond exactly to those of Garner, 1974, but the idea is related). Integral feature pairs conjoin automatically, while separable pairs need attention to be conjoined. Which feature pairs are which is an empirical question (and little if any research directly toward "integral" pairs has been carried out).

Treisman and Gelade (1980) carried out several empirical tests (using what are considered to be separable features) that supported and illustrated the main points. (1) Visual search for single features (or integral conjuctions, but this has not been tested) should be insensitive to load, but search for conjuctions of two features should be serial in nature, as attention is shifted from item to item in turn. (2) A discontinuity in texture between two regions of stimuli should be evident to find for a single feature discontinuity, but difficult for a conjuction. (3) In the absence of attention, (separable) features should be free floating and sometimes recombine into illusionary colors, just as Smith and Kemler Nelson (1984). (4) When single feature targets are found in visual search, their spatial position might be inaccurate since detection need not require focul attention; conjuction targets require attention and should be well localized. (5) Grouping of identical items together in a display should allow search for conjuctions to proceed group by group, while search for single feature targets should remain unaffected by display size (Treisman, 1982).

Each of these predictions was given empirical support, (1), (2), and (4) by Treisman and Gelade (1980), (3) by Treisman and Schmidt (1982), and (5) by Treisman (1982). Certain additional results should be mentioned because they extend these predictions and findings. First, Egeth, Virzi, and Garbart (1984) showed that the search for conjuctions is not really serial. Instead, the subject chooses one feature (presumably the easiest) to segregate the display into two regions and then serially searches the items within the relevant region for the other feature. Treisman and Gelade (1980) and Treisman et al. (1977) had subjects search for conjuctions (e.g., red O) in distractors each of which contained one of these values (e.g., black Os and red Ns). The number of each type of distractor was highly correlated with the display size. Egeth et al. (1984) covaried the numbers of each type of distractor and also instructed subjects to attempt to search just within the relevant color, or the relevant letter. The results are given in Figure 11.25. The curve labeled "confounded" had equal numbers of distractors of both types. The unconounded cases (i.e., one type of the type to be attended, regardless of display size (e.g., "Attend-to-red" cases had three red letters, possibly including the target). Attending to red was easier than attending to O, but clearly search could be limited to the relevant subset of red. In fact, the "attend-to-color" findings are very much like the single feature findings of Treisman and Gelade (1980).

These search results are like those of Green and Anderson (1985), Smith (1982), and Carter (1985), in showing that search could be restricted to the relevant color subset. However, Carter (1982) showed that the background elements did begin to have an effect when color discriminability was reduced, findings that may be analogous to the letter discrimination results that were not evident in the color cases (Carter, 1982). (6) When single feature targets are found in visual search, their spatial position might be inaccurate since detection need not require focal attention; conjuction targets require attention and should be well localized. (5) Grouping of identical items together in a display should allow search for conjuctions to proceed group by group, while search for single feature targets should remain unaffected by display size (Treisman, 1982).

There is a problem in the theory that the right hand side of the display is not evenly divided by the pointer. A problem with the theory that is carried over from the earlier work is the model of 1981. The model of 1981 used stimuli like those shown in Figure 11.15. Subjects searched for a plus sign in a circle. Examples of the target absence trials are given in the figure. Illusory conjuctions were seen as the result of false alarms in A and B relative to C and D. However,
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more false alarms occurred in A than B, showing that features were not conjoined as often across the evident perceptual groups. There are many possible interpretations of these findings, but they suggest that perceptual grouping can be at least as primitive and early a process as feature extraction, a prediction of the theory (Treisman, 1982). It is likely that automatic encoding of displays goes on in parallel at several levels at once, without the necessity of focal attention, but that focal attention is sometimes needed to "glue" together the low level features and preserve them better for accurate future report. This notion is supported by findings of Prinzmetal and Millis-Wright (1984) showing that report of the color of a preselected target is affected by the word-like qualities of the letter strings containing the target.

A related but somewhat different finding concerning illusory conjunctions was reported by Virzi and Egseth (1984). They showed that illusory conjunctions occur not just for unattended "simple" features, but even for meaning. For example, subjects presented with the word BROWN in red ink, and the word HEAVY in green ink, both in unattended locations, would sometimes report, incorrectly, that the word RED, or the ink color brown, had appeared in the display. It may be that these are "memory" rather than "perception" errors, but memory and perception can be notoriously difficult to disentangle, so that at least illusory conjunction errors should be interpreted with some caution. If the Virzi and Egseth data are accepted as demonstrating perceptual illusory conjunctions, then the features of the system must in this case be quite "deep" and in fact be a conjunction of elementary features. This could be consistent with the Treisman approach, since a word is part of general knowledge, which can serve to conjoin its features automatically.

It is still somewhat early to assess feature integration theory. When applied to explain the slopes of visual search functions the theory may have some difficulties. As discussed earlier in this chapter, in the section on stimulus factors in visual search, Duncan, Humphreys, and their colleagues have argued the theory has trouble accounting for certain results, for any simple choice or features. They also suggest that factors of similarity between sets of targets and distractors can handle the search findings that seem to support the theory. Further research is needed to explore these issues.

Some Observations about Features

Obviously much research is being carried out to explore the relation of stimulus attributes and combinations to perceptual organization and selective attention. At this writing it would be premature to try to draw general conclusions, since the issues and results are changing and evolving. A few observations are worth making, however. First, despite a century of research aimed at establishing the features and dimensions that make up stimuli, we are still a long way from firm answers. At present it is not possible to predict a priori what the stimuli in a given setting, what will be their salient features, and how the features will affect attention or perception. Instead, studies using attentional and perceptual tests are carried out on such stimuli and the results used to infer the features that must have been present and their nature. Second, there is no good reason to think that the results used to support global processing, global feature precedence, automatic conjoining of features, and automatic perception of complex objects are inconsistent with the results used to support feature integration theory. Since prior knowledge can act to conjoin features in the theory, these results may well be consistent with the theory. Third, feature integration theory may have some difficulties explaining the slopes of visual search functions unless other mechanisms are posited.

Finally, it is safe to conclude that, however we ascertain the nature of the features in a given task, those features that are automatically extracted (or otherwise activated) by the perceptual system and made especially salient to the decision system have enormous effects upon both performance and subsequent attentive processing.

Multiple Resource Pools

Much of the research discussed in this chapter has been predicated upon the assumption, explicit or implicit, that there is a single pool of central resources that is allocated to or shared among the processing needs of the system. Nonetheless, there may be reasons to think that different tasks or task components may require different resources. The basic idea is that different resources (if these exist) are not always substitutable. When Resource A is in short supply, the deficit cannot necessarily be made up by Resource B, even if Resources B is underutilized. Demonstrating the existence of multiple resources is not easy, but is possible if one is not concerned with the nature of the resources in question. Some "resources" are not very interesting. For example "right arm movement" could be viewed as a resource if needed for several tasks requiring such movements; "left leg movements" could be another resource. Even if left leg movement is not needed in a
particular experiment, the availability of this resource would not much help a subject faced with the need to make three different, incompatible, right and left arm movements simultaneously. These sort of motor response constraints could be ruled out of consideration, but automatic responses and processes could exhibit similar patterns of independence and incompatibility, making interpretations in terms of simultaneous processing problematic. Such considerations must be kept firmly in mind.

How may one assess the existence of multiple resource pools? This is a most subtle research issue. Consider one proposal: "The central capacity notion cannot withstand the finding that when the performance of a certain task is disrupted more than the performance of another one by pairing either of them with a third one, it is nevertheless disrupted less by a fourth one." Navon & Gopher, 1979, pg. 229. This may be restated as follows. Let \( P(T_i) \) be the performance of task \( i \) alone, and \( P(T_i + T_j) \) be the performance of task \( i \) when it is paired with task \( j \). Then,

\[
P(T_i) - P(T_i + T_j) < P(T_i + T_j)
\]

(1)

How can such a pattern occur? One possibility is that \( T_i \) is at least partially incompatible with \( T_1 \), but not \( T_2 \), and that \( T_4 \) is at least partially incompatible with \( T_2 \), but not \( T_1 \). If \( T_1 \) and \( T_3 \) must share one central resource, and \( T_2 \) and \( T_4 \) some other central resource, the above outcome would occur. Unfortunately \( T_1 \) and \( T_3 \) could share a resource as uninteresting as muscle availability (e.g. \( T_1 \) and \( T_3 \) require left and right eye movements, respectively), and the same could be true for \( T_2 \) and \( T_4 \).

This problem is pretty much universal. One can establish, using the above criteria or others, that multiple resources are required, but separate means must be used to establish the nature of those resources. The difficulty of this latter task must not be underestimated.

We shall return to the question of tests for multiple resources after considering an empirical study. Friedman, Polson, Dauoe, and Gaskill (1982) tested the hypothesis that the left and right hemispheres have separate, limited-capacity resource pools that are not mutually accessible, so that different tasks can overlap in their resource demands either completely, partially, or not at all.

We shall present a simplified description of their Experiment 2 in the hope that clarification will be gained without much loss of accuracy. Subjects were chosen on the basis of pretests (e.g., righthandedness) to insure they processed verbal material in their left hemisphere. Presentation of material to their right fields produces initial processing in the left hemisphere, and vice versa, although the other hemisphere could eventually carry out processing after information is transmitted from one hemisphere to the other. Two tasks were to be carried out together: (1) Three five-letter nonsense words were presented to the right visual field (i.e., left hemisphere). Those were to be studied and held in memory while a second task was carried out. (2) Two three-letter nonsense words were presented very briefly for a same-different judgment, in which accuracy of response was measured. The pair of words was presented either to the right or left visual field, and the judgment required was "name" or "physical" identity (e.g., name match: DAF--DAP; physical match: DAF--DAP). Finally, subjects were to emphasize either the memory task or the matching task.

Some results are given in Figure 11.27, in terms of the loss or decrement from the single task control conditions to the dual task conditions. Note that when the same hemisphere must carry out both tasks (left panel) there were clear indications of resource sharing. As emphasis is shifted to the memory task, memory performance went up and matching performance went down. On the other hand, emphasis made no difference when different hemispheres were presumed to be carrying out the tasks (right panel). One can interpret these findings in terms of different resource pools: Sharing is necessary when both tasks require the left hemisphere, but not when each task can be carried out by a separate hemisphere. Of course, even when different hemispheres are utilized, dual task performance is worse than single task performance (right panel), so at least there is a concurrence cost.

There have been quite a few other attempts to establish the nature and number of multiple resources (e.g., Hirt & Kalmar, 1987). Wickens (1988) and his colleagues have tried to argue that different resources exist for different modalities, because auditory and visual tasks can be carried out more easily together than auditory and auditory or visual and visual tasks. Some studies show this to be the case but others do not; the exceptions might be due to other factors that help when both tasks are in one modality. For example, when both tasks are in one modality attention switching between modalities is not needed. Another possibility is that some sort of helpful integration of two tasks can occur when they are in the same modality (Wickens, Fracker, & Webb, 1987).

It seems likely that the establishment of multiple resources in particular studies will not prove too useful for theorists of attention until general models are developed that will specify the nature of the resources, that will explain the way in which they will be used in carrying out specific tasks, and that will allow predictions of multiple task performance in new situations. It would be useful for the development of such a model if evidence could be found allowing a choice to be made between a view like that of Kahneman (1973), in which there is one central resource and many "satellite" resources (like those concerned with motor movements, or automatic perceptual mechanisms), and a view that of Wickens (1988) in which there are multiple central resource pools (possibly overlapping partially). An example of the latter might be found in the theory of Friedman et al. (1986). Wickens (1984) concludes that a decision between such views is most difficult if not impossible, but any discussion is beyond the scope of this chapter (see also Navon & Gopher, 1980; Navon, 1984). It is certainly safest to conclude that multiple resources exist, but whether more than one of these could properly be viewed as a central resource is presently an open question.

![Figure 11.27](image.png)
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conclusions reached, would not be different in any important way were the auditory studies added to the coverage in the chapter.

The most significant section in the chapter is the relationship between attention and memory. These are as inextricably intertwined as automatic and attentive processes, and many theorists have treated them as a single topic (cf. Norman, 1968; Underwood, 1976). Atkinson and Shiffrin (1968) dealt extensively with "control processes," which was another term for attentive processes, in the domain of memory. Since decisions, retrieval mechanisms, coding processes, rehearsal and other similar processes represent the use of attention, virtually the entire field of memory falls in principle into the proper domain of attention. Studies whose main import lies in memory have been excluded for the most part from this chapter, primarily in consideration of space limitations, but also because other chapters in this handbook deal with various manifestations of memory.

Many other topics have been excluded as well. A nonexhaustive list of these includes: (1) The intensive aspects of attention, including arousal, roughly revolve around the possibility that attentional capacities are being raised or lowered by the subject (in accord with environmental demands) or will be raised or lowered by influences not under the control of the subject (e.g., Kahneman, 1973).

We have tried to discuss tasks for which it is not unreasonable to assume that attentional resources are being utilized at, or close to, their maximum level. (2) Vigilance or sustained attention tasks require the subject to continue to perform (or detect) over long periods of time. Much research has been carried out to study decrement in performance that takes place over time (e.g., Broadbent, 1971; Parasuraman, 1984). (3) Physiological and psychophysiological correlates of attention. (4) Effects of environmental stress on attention and performance. (5) Automation and performance in motor skill acquisition and performance. (6) Individual differences in attentional selectivity and sustained attention. (7) Attention in non-human organisms and animal learning. (8) Attentional aberrations as a factor in mental disease. (9) Attention and automatism in social perception, judgment and memory. Introductions to these topics can be found in the references given at the outset of this chapter.

FINAL REMARKS

Throughout this chapter, most of the studies presented in detail are based on search paradigms. There is a good reason for this choice. Search paradigms have been the most studied in the experimental literature on attention; although there remain many perplexing questions concerning search, the processes involved in this paradigm are better understood than those from any other. Most important, search is one of the few paradigms where automatic and attentive processes have been disentangled to any substantial degree. The treatment in the present chapter emphasizes more heavily than most the separate roles of automatic and attentive processes, and their interaction. It is this author's firm opinion that little empirical or theoretical sense can be made of attentional phenomena without a firm grasp of the symbiotic roles played by automation and attention. This opinion would hardly have been a surprise to the pioneering psychologists concerned with attention near the turn of the century. Perhaps the point has not received the prominence it merits in some modern treatments, but is more overt or lower by the subject (in accord with environmental demands) or will be raised or lowered by influences not under the control of the subject (e.g., Kahneman, 1973).

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REFERENCES

Are there any global conclusions that can be reached concerning some of the traditional issues that have driven modern attentional theory? At the cost of vast oversimplification, matters might be summarized as follows: Performance, but not attention, may be divided successfully through the use of development of automatic processes, and successful focusing takes place through the application of limited attentive resources. Failures to focus at all are due to an inability to select inputs at "late" levels of processing (at least without special training), but momentary interruptions of focusing are due to automatic mechanisms involving and interfering with the attentive system itself. Selection of inputs to process is easiest when the selection is based on simple, primitively features of the type that are closely related to the operations of the peripheral sensory systems. The limitations of the attentive system, however, are not restricted to any particular locus in the processing system, and appear whenever and wherever attentive resources are used to facilitate performance. Behavior in general is accomplished by limited, perhaps serial, attentive processes operating in parallel with numerous automatic processes, with the two systems passing information back and forth at all levels of analysis.

REFERENCES


Cherry, E.C., & Taylor, W.K. (1964). Some further experiments upon the recognition of speech with
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