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ATTENTION

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CONTENTS

This is a selective review of attentional research, primarily that involving the detection or identification of visual targets. Such work is central to the study of attention and currently among the most active areas of attentional research. By restricting the review to this narrower focus it is possible to describe the studies in more detail, raise some critical questions about their interpretation, and point out their relation to earlier research. While the studies reviewed are primarily behavioral, a brief description of some important neurological work is also presented.

WHAT IS ATTENTION?

Although the term attention is often used as if its meaning were self-evident it has remained a remarkably elusive concept. There are overt forms of attending or orienting that can be studied directly, such as the way we shift our gaze to bring one object or another into view. There are also covert forms of attending, whereby we choose to listen to one voice or another among the babble of simultaneous voices at a party, or attend to different parts of a visual image without moving our eyes. The studies reviewed here are primarily concerned with overt forms of attending. I argue that the fundamental empirical bases for the concept of covert attention are the processing tradeoffs one often seems to make when simultaneously presented with multiple "sources" of information. By tradeoff I mean that better processing of one source seems to require poorer processing of another. The covert adjustments one makes to adopt a particular tradeoff I will term an *allocation of attention*. For example, the multiple sources of information might be the simultaneous voices at a party, or the individual letters in a tachistoscopically viewed letter matrix. Attempting to process ("attend to") a particular voice, letter, or row of letters, defines a particular allocation of attention.

It should be emphasized that the processing of simultaneously presented sources of information does not always reflect a need for processing tradeoffs. It sometimes seems possible to process sources simultaneously as well as they can be processed singly. In such cases the simultaneous processing is said to require less than one's "attentional capacity," or the processing of at least one source is said to "occur in parallel," "automatically," "pre-attentively," or "without needing attention."

In any case, the manner in which people process simultaneously presented sources of information, "shared allocation of attention," the degree to which they can process one source and ignore another, "focal allocation of attention," and the manner in which they shift from one allocation of attention to another, "attention switching," are all central to the study of attention.

PROCESSING TRADEOFFS AND SET-SIZE EFFECTS

In discussing experiments involving multiple sources of information it will be useful to denote n such sources by S_1, S_2, . . ., S_1n. In the simplest paradigm there may be only two sources, S_1 and S_2; $n = 2$—for example, two simultaneous voices or two positions in a visual display. In such cases it is possible to characterize a subject's processing options by what has been variously referred to as an *attention operating characteristic*, AOC (Kinchla 1969; Sperling & Melchner 1978), a *performance operating characteristic*, POC (Norman & Bobrow 1975) or, in a slightly different form, a *cost-benefit analysis*

(Posner & Boies 1971). The AOC form of representation is illustrated in Figure 1a, which shows three ways (I, II, III) in which a subject's ability to process each of two sources might be related. In some studies "processing" is assessed in terms of accuracy; in others, in terms of speed (the faster a subject can respond to information from a source, the better the processing). The open points in Figure 1a indicate the quality of processing when a subject is directed to "attend to S_1 only" (ordinate) or "to S_2 only" (abcissa), so called "focal attention" instructions. The solid points indicate how well each source is processed when the subject is instructed to "attend to both S_1 and S_2"—"divided" or "shared attention" instructions. Note that Curve I indicates that S_1 and S_2 can not be processed simultaneously as well as either can be processed alone, while Curve II indicates a similar but less severe cost of "sharing attention." Usually a subject can also be induced to perform at intermediate points if instructed to "pay attention to both sources, but more to one than the other." Curves I and II, then, are examples of the processing tradeoffs, AOC functions, which underlie the concept of attention. A subject can operate at any point along the function by adopting a particular allocation of attention, but improved processing of one source inevitably means poorer processing of the other.

In contrast, note Curve III in Figure 1a. Here there is no evidence of a processing tradeoff: The subject can process S_1 and S_2 at the same time (solid point) as well as either source alone (open points). As will be shown, such an absence of a processing tradeoff, plus the often involuntary nature of such processing, underlies the concept of "automatic" or "pre-attentional" processing.

A currently popular method of studying attentional processes uses visual search tasks in which subjects are asked to decide rapidly whether or not an n-element visual array contains a particular "target" element. In some cases response times increase with n, a so-called *set-size effect,* which is often interpreted as implying a serial (one-after-another) processing of the n elements—i.e. a successive "attending" to each element. In other cases response times are independent of n, which is often taken to imply parallel (simultaneous) processing. The relationship of such arguments to those based on AOC functions is illustrated in Figure 1b, which replots the same three sets of hypothetical data (I, II, and III) shown in Figure 1a. In Figure 1b the two "sources," S_1 and S_2, correspond to the elements in a two-element array that must be "searched" for the presence of a target, perhaps a left element and a right one. Here the data labeled I and II are said to indicate a "set-size effect": Subjects take longer to evaluate both elements for the presence of a target than when told to evaluate only one of the elements (e.g. "the left one only"). In contrast the data labeled III in Figure 1b indicate no set-size effect: A two element array can be "searched" for a target as rapidly as a single-element array. Thus processing tradeoffs and set-size effects are essentially similar.

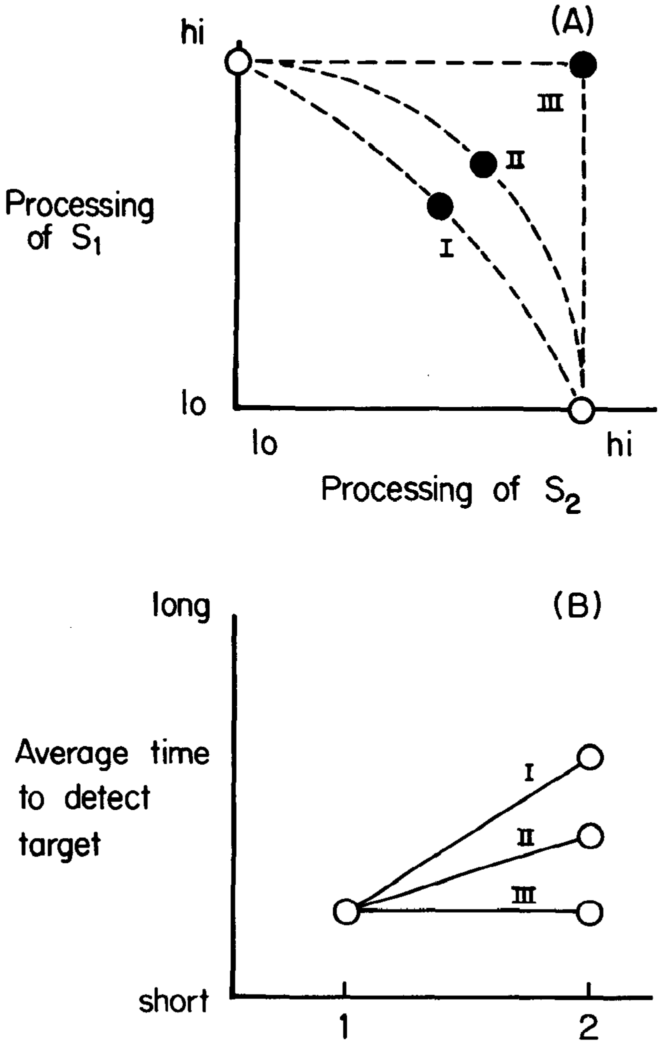

Figure 1 Three illustrative performances (I, II, III) represented in the form of (*a*) an attention operating characteristic and (*b*) reaction time as a function of set-size. Only performances I and II indicate an attentional or set-size effect. Performance III is often characterized as indicating "pre-attentive," "parallel," or "non-attentional" processing.

Their presence suggests an attentional process and their absence a "pre-attentional," "non-attentional," or "automatic" one. A major advantage of the representation shown in Figure 1b is that it can be used when n is greater than 2. However note that in Figure 1b response times are averaged across sources so the time to detect targets in specific sources (e.g. positions) is suppressed.

Before going on to consider research on visual search, it seems useful to show how a cost-benefit analysis (Posner & Boies 1971; Juola et al 1991) is simply another way of representing the processing tradeoffs revealed by AOC functions. Such an analysis is illustrated in Figure 2, which presents hypothetical data from a divided attention task, first in the form of an AOC function (Figure 2a) and then as a cost-benefit analysis (Figure 2b). These data are typical of those obtained in divided attention tasks where a subject monitors two sources of information (S_1 and S_2) for the occurrence of a target or signal (e.g. a brightness increment at one of two locations on a visual display), and where reaction time is the primary dependent variable. The three performances (data points) defining the AOC function in Figure 2a are the sort that can be obtained by varying the relative frequency of signals from each source. Specifically, suppose signals occurred at S_1 with probability P_1 or at S_2 with probability P_2, with $P_1 = 1 - P_2$. The three data points in Figure 2a are representative of those that might be obtained when P_1 equalled .8, .5, or .2. It is as if the subject processes S_1 more rapidly if signals are more likely at that source ($P_1 = .8$), processes S_1 and S_2 about equally well if they are equally likely to contain a signal ($P_1 = .5$), and processes S_2 faster if it is more likely to contain a signal ($P_1 = .2$). Naturally, error rates would have to be evaluated to insure these changes in mean reaction time reflected more than a "speed-accuracy tradeoff" (RT and error rates would have to be positively correlated).

Figure 2b shows how the same data might be represented as a cost-benefit analysis (how quickly the subject can respond following the occurrence of a signal). Here the value P_1 (.8, .5, or .2) is normally indicated by a cue prior to each test trial. The cue is said to be "valid" if a signal occurs at S_1 when $P_1 =$ .8, or at S_2, when $P_1 = .2$, or "invalid" if the signal occurs at the less likely source. The cue is considered to be "neutral" when $P_1 = .5$. Figure 2a shows the average reaction time to signals given valid (V), invalid (I), and neutral (N) cues. Using the mean reaction time to signals with neutral cues as a reference point, one can define, the "gain" (reduced RT) when the cue is valid and the "cost" (increased RT) when the cue is invalid. If cues indicating which source is more likely to yield a signal produce *no cost or gain,* there is *no evidence of any attentional process* (just as with the data labeled III in Figure 1a and 1b).

It is argued here that the AOC/POC form of analysis is preferable to cost-benefit analysis on the following grounds. There is no reason to assume the neutral cue ($P_1 = .5$) actually produces an equal "allocation of attention," whereas the AOC representation allows one to assess this. The three data values in Figure 2b are the result of *averaging* responses to targets in S_1 and S_2 for valid, neutral, and invalid cues, whereas all six measures of the dependent variable are represented by the coordinates of the three data points in Figure 2a. And finally, the subject in a cost-benefit analysis is never given

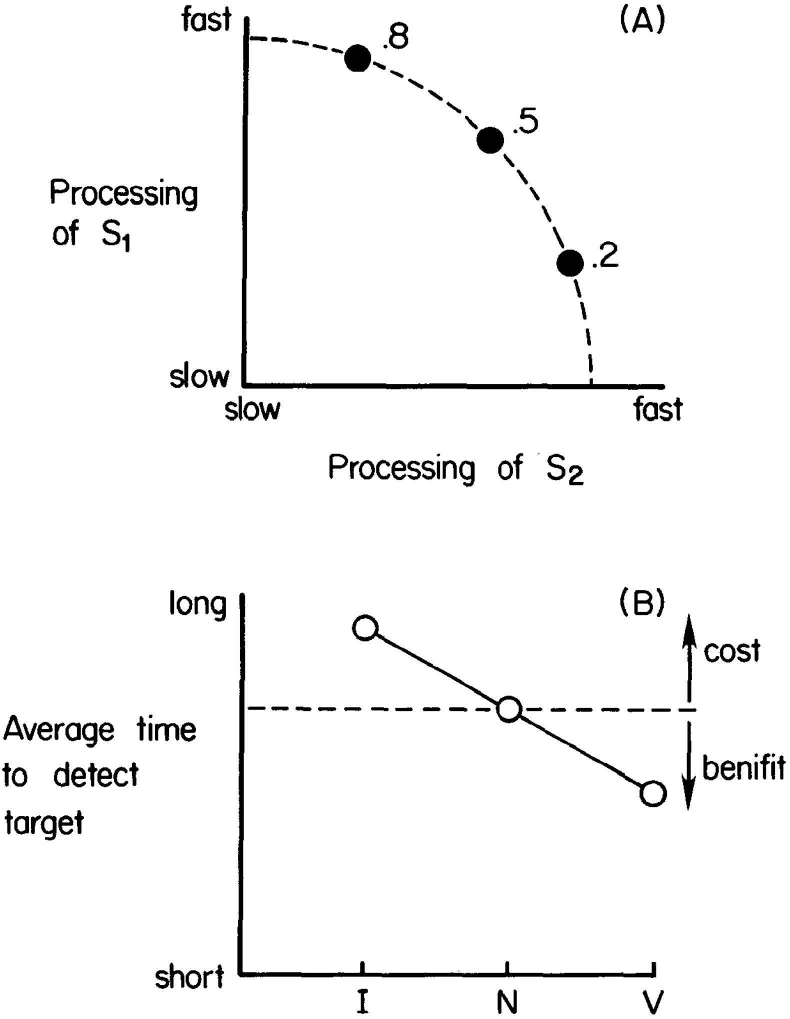

Figure 2 (*a*) An AOC function based on performance when targets occurred in S_1 with probability .8, .5, or .2 as indicated on the graph. (*b*) The same data shown as a "cost-benefit analysis" when cues were valid (V), invalid (I), or neutral (N). See the text for further discussion.

the opportunity to "attend" exclusively to either source as they did for the AOC functions in Figure 1 (open points). In the cost-benefit analysis it is often assumed that subjects always "attend" to the source that has the .8 probability of containing the signal. Yet much research on statistical "guessing games" (see Neimark & Estes 1967) suggest that subjects would actually "match": attend primarily to the more likely source 80% of the time and to the less likely 20%. This of course raises the question of whether subjects can actually "share attention" or must "switch" in an all-or-none fashion. In either case, directly comparing performances in focal and divided attention tasks seems necessary in order to assess the true "cost" of dividing attention. Finally "costs" and "benefits" are often compared directly as if they were linearly related to some underlying cognitive variable. Yet it seems clear that under extreme speed pressure it may be much harder for a subject to reduce reaction time than to increase it; e.g. 100 msec of "gain" should not be equated with 100 msec of "loss."

VISUAL SEARCH

Figure 3 shows some search data reported by Steinman (1987). Subjects had to search *n*-element arrays for a target element. Each "element" was formed by three parallel lines and could vary along the two dimensions illustrated in Figure 3a: separation, equally separated or not, and orientation, lines vertical or slightly tilted. Search times for various targets are shown in Figure 3b. If the target was defined by a value on one dimension (e.g. "tilted"), the median time to detect a target appeared to be independent of the set-size. However, if the target was defined by a conjunction of values on both dimensions (e.g. "tilted and equally separated"), and some of the nontargets included each of these values alone, there was a strong set-size effect.

The general pattern of results illustrated in Figure 3 has been reported by many investigators using a wide variety of stimuli—i.e. a set-size effect for targets defined by the conjunction of values on two dimensions, and none for targets defined by a value on one dimension. A highly influential explanation of these results has been advanced by Treisman and her associates (Treisman 1977, 1982, 1988, and Treisman & Sato 1990). Her *feature-integration theory* depicts the conjoining of features as a process that "requires attention." Thus searching an *n*-element array for a conjunction target requires a successive shifting of attention from one element to the next. This accounts (among other things) for the linear set-size effects often found with such targets: Equal increments in set size produce equal increments in response time. Furthermore, the slope of the search function for "detect" responses is often half that for nondetect responses, as if the search process was serial and self-terminating (so that, on average, only half the array elements need be searched to detect a target). In contrast, searching for a target defined by a value on only one dimension seems to involve a parallel ("pre-attentive") process, since there is no set-size effect (the search function is flat).

The idea that one perceives complex objects by "conjoining" separately processed sensory dimensions stems partially from the discovery of specialized neural "channels" (modules or subsystems) that appear to process specif-

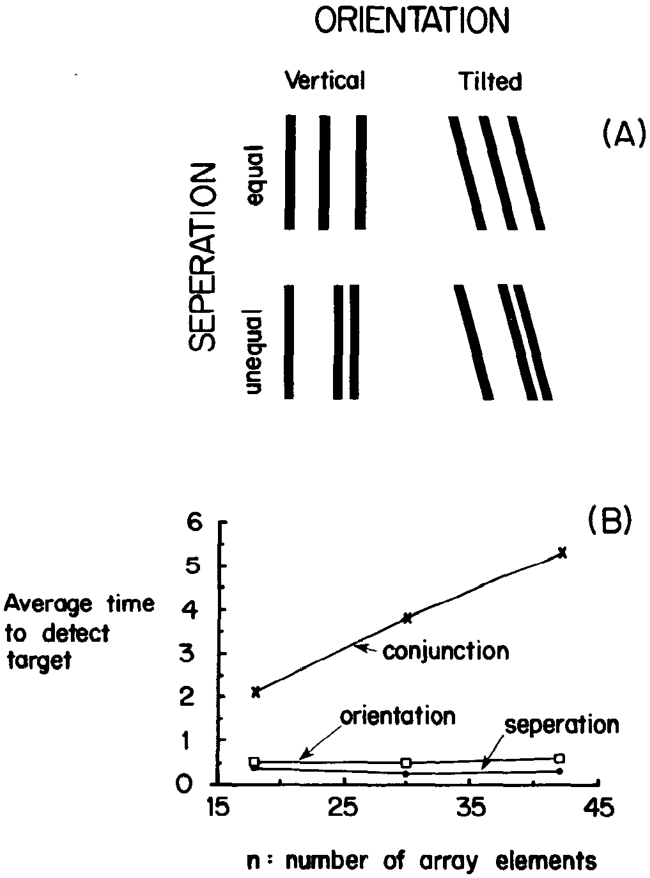

Figure 3 (*a*) The four types of stimuli defined by combinations of values on two dimensions. Each array contained *n* such stimuli. (*b*) Search times for targets defined by a value on one stimulus dimension (orientation or separation), or by a conjunction of values on both (e.g. tilted and equally separated). Data from Steinman (1987)

ic aspects of a visual stimulus, such as color, form, and motion (see Graham 1985; Livingston & Hubel 1987). Search for a target value on a single dimension might involve the output of only one such channel, while search for a conjunction target would involve the conjoining of outputs from two independent channels. This notion is also consistent with a finding by Grabrowecky & Treisman (see Treisman 1988:212–14) that the probability of detecting a conjunction can be predicted from the product of detecting the individual values.

Another aspect of Treisman's theory is her explanation of *conjunction errors*, the illusionary perception of improperly conjoined stimulus values—

e.g. "seeing" a red candle in a green holder as a green candle in a red holder. Such errors of visual perception have been demonstrated with a wide variety of stimuli and are most likely to arise with objects outside the region you are told to attend to, or when you are asked to"spread your attention over the entire visual field." It is as if accurate conjunctions require focal attention (Julesz 1986; Treisman & Gormican 1988; and Treisman & Paterson 1984).

Treisman's is not the only interpretation of set-size effects in visual search. It is true that a linear set-size effect can be interpreted as a serial process in which the evaluation of each additional element takes the same amount of time; but this does not rule out a parallel-processing interpretation—e.g. one in which each additional item is processed at the same time but at a lower rate, as if a limited resource were being divided among more elements. Classic papers on the difficult problem of distinguishing parallel and serial processes are those by Townsend (1971, 1976, 1990).

Another problem with interpreting set-size effects as implying a serial shifting of attention can be illustrated as follows: Suppose a subject viewed n briefly exposed letters, presented in slow succession at the rate of one letter per second, and then reported whether at least one of the letters had been a target letter F. Note that subjects can allocate all of their attention to viewing each letter, since the letters occur sequentially rather the simultaneously. Yet it has been shown that so long as each letter is presented briefly enough, the accuracy of the subjects' decisions diminishes as n increases—that is, there is a set-size effect on accuracy (Eriksen & Spencer 1969). A similar effect is obtained if a subject listens to n successively presented bursts of white noise and then reports whether at least one of them was accompanied by a weak tone signal (Kinchla 1969).

An explanation of these effects in terms of the "noise" or "confusability" contributed by each array element can be made in terms of the following integration model (this is a slightly simplified version of a model presented in Kinchla 1969, 1974):

1. Let each element S in an n-element array evoke a "subjective impression" X_i ($i = 1, 2, \dots n$).
2. Let each X_i be a Gaussian random variable with variance σ^2, and an expected value of one if S_i is a target, or of zero if S_i is a nontarget.
3. Let the subject report a target if an "integrated impression" equal to ΣX_i exceeds some response criterion C.

It can easily be shown these assumptions imply that a subject's ability to discriminate between arrays containing one target and those containing none can be characterized by the following "d-prime" measure (see Green & Swets 1966):

$$d' = 1/(n\ \sigma^2)^{1/2}$$

Note that discriminability, d', diminishes as the square-root of n increases, a set-size effect. This is due to the "noise" (σ^2) or "confusability" contributed by each display element, which tends to obscure the single target's contribution to the integrated impression, ΣX_i.

The point to be made here is that a simultaneous presentation of the n-elements in an array could produce the same set-size effect, even if there were no need to attend serially to each of the n-elements. This is why Kinchla (1969) and Shaw (1982) argued that *an "attentional" explanation is required only if the set-size effect on accuracy with simultaneous presentation exceeds that obtained with sequential presentation*. In fact Eriksen & Spencer (1969) found no difference in a subject's accuracy with (virtually) simultaneous or slow sequential presentation. Thus those data do not suggest any "attentional" problem in processing simultaneously presented arrays, only the same confusability problem encountered with sequentially presented arrays. Further evidence for this view is presented by Shiffrin & Gardner 1972.

It should be noted that the preceding model also predicts a *redundant targets effect* when more than one target appears in an array. Specifically, if an n-element array contains t targets ($t = 1, 2, \ldots n$), a subject's ability to discriminate it from arrays containing no targets is given by:

$$d' = t/(n\ \sigma^2)^{1/2} \qquad 2.$$

Again, the improvement in discriminability with redundant targets is explained solely in terms the increased expected value of the integrated impression (ΣX_i), not to an increased likelihood of "attending" to a target.

These issues have also been dealt with in terms of reaction time in studies by Shaw (1978, 1982, 1984), van der Heijden et al (1984), and Ulrich & Giray (1986). Two general types of model have been studied—*race models* and *integration models*. The simple model we have just considered is a type of integration model, where information about each element is combined or integrated prior to any decision. In contrast, race models represent each element as being independently processed, with a positive search response made as soon as any element is identified as a target. To a large extent the effects of set size and redundant targets can be accounted for in terms of either type of model (see Bundesen 1990; Miller 1986; Shaw 1982). However, in some studies certain properties of the latency distribution have been inconsistent with the fully independent race model (see Miller 1982).

Such findings lead Mordkoff & Yantis (1992) to propose an "Interactive Race Model" that is somewhere between a fully independent race model and a conventional integration model. While elements are fully processed in separate channels, with an affirmative response made as soon as any channel detects a target, the channels are not completely independent. For example, if one channel identifies an element as a nontarget it can influence the processing in another channel. This is particularly important if the elements in an array are correlated, as they are in most visual search tasks. This can be illustrated by a search task involving two-element arrays. Suppose half the arrays contained one target, and the other half no targets, so that prior to a trial, each element in a randomly selected array had a one fourth probability of being a target. Note that as soon as one of the four elements was processed to a point where it was clearly a nontarget, the remaining element would then have a one third probability of being a target. Thus identifying one element as a nontarget contains information about the other element. It is primarily this correlational information that Mordkoff & Yantis propose the channels share, rather than a complete integration of impressions. They also assume that identification can activate common memory representations to produce interactions. This sort of model provides yet another way of interpreting set-size and redundant-target effects.

In addition to the preceding general considerations several other types of evidence raise questions about Treisman's original feature-integration theory in which set-size effects are interpreted as the product of serial shifts in attention.

There is evidence that certain multidimensional targets may have "emergent" or "higher-level" properties that also produce flat search functions ("allow one to search for them in parallel"). For example, Enns (1990) employed drawings of many three-dimensional cubes oriented in one direction and asked subjects to search for a target cube oriented in a different direction (see Figure 4). The subjects yielded flat search functions and reported the target seemed to "pop out" of the display, easily discriminable from the differently oriented cubes. Similar results have been obtained with other relatively complex targets defined by the direction of lighting (Enns & Rensick 1990) or gradients of shading (Ramachandran 1988). Treisman & Paterson (1984) also obtained flat search functions when they had subjects search for a triangle among clusters of component lines and angles that were not joined. They concluded that the emergent Gestalt property of "closure" allowed the triangle to be searched for in parallel. However Treisman & Gormican (1988) were unable to produce flat search functions when they formed potentially emergent forms such as intersections and junctions formed by two straight lines.

Several investigators have found virtually flat search functions for a variety of conjunction targets so long as the values on each stimulus dimension were highly discriminable (McLeod et al 1988; Nakayama & Silverman 1986ab; Steinman 1987; Wolfe et al 1989). Phenomena of this sort led some investigators to contrast feature and conjunction searches in terms of the discriminability of targets and distractors. It was pointed out that targets are

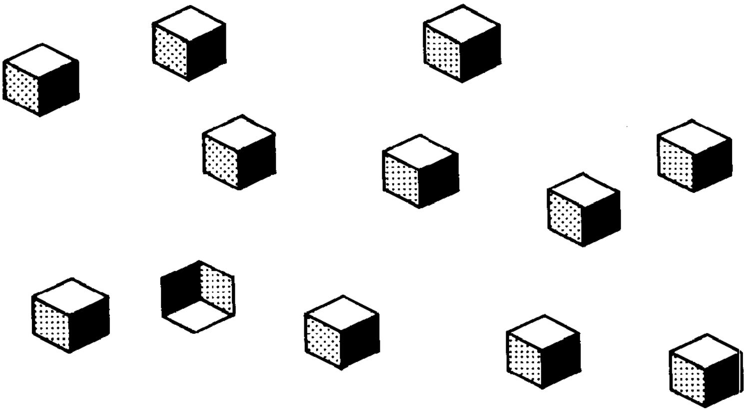

Figure 4 Enns (1990) obtained flat search functions for complex forms when targets were defined by their apparent three-dimensional orientation. They seemed to "pop out".

generally less discriminable when embedded in heterogeneous sets of distractors than they are in homogeneous sets (Duncan & Humphreys 1989; Humphreys & Riddoch 1989; Quinlan & Humphreys 1987). For example, the three rows of symbols in Figure 5 represent three arrays, each containing a target letter A flanked by two distractors. The top two arrays (rows) have homogeneous distractors (only one type), while the bottom array has heterogeneous distractors (more than one type). Note that the target in the top two arrays is distinguished from the distractors by a single "feature": the right diagonal component of the A in the top array, and the horizontal component in the middle array. However, neither "feature" alone is sufficient in the bottom array; only when both "features" are present (a "conjunction") can a viewer be sure the symbol is the target letter A. Thus increased heterogeneity among distractors may require more extensive processing to distinguish targets, since it may involve a search for conjunctions of features. Differences among distractors have also been termed "internal noise," while differences between distractors and the target have been termed "target salience." Thus serial search is necessary when internal noise is high and salience low (Wolfe and Cave 1990).

These findings have suggested alternatives to Treisman's original feature-integration theory. For example, Wolfe et al (1989), Cave & Wolfe (1990), and Wolfe et al (1990) proposed *guided-search* models similar to one proposed earlier by Hoffman (1978, 1979). These models depict a subject as guiding a conjunction search by (at least partially) limiting search to those elements that had one of the conjoined features. For example, a serial search for a red triangle among red circles, green circles, and green triangles, might

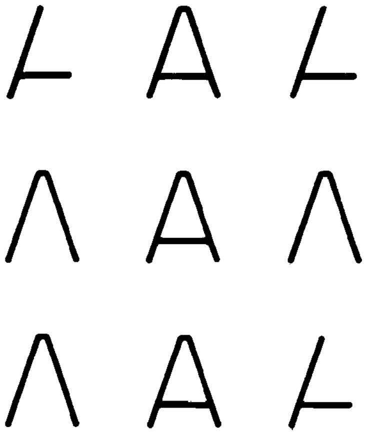

Figure 5 The three rows correspond to three arrays containing the target letter A flanked by distractors. In the top and middle array (row) the distractors are homogeneous, in the bottom row heterogeneous.

only evaluate red elements or triangular elements, thereby not wasting time on green circles. High discriminability of the values on each dimension should enhance the subject's ability to process selectively only values common to the target (see Duncan & Humphreys 1989; Humphreys & Riddoch 1989). Treisman & Sato (1990) have proposed a similar elaboration of Treisman's original feature-integration theory except that they emphasize a selective search based on an "inhibition" of irrelevant features rather than the "facilitation" of relevant ones suggested by Wolfe et al (1989, 1990). Nevertheless, the ideas are essentially the same: Search is limited to elements having at least one of the conjoined values.

Another complexity in evaluating feature-integration theory is that most visual-search studies employed large sets of elements (*n* greater than 10). However, Houch & Hoffman (1986) and Pashler (1987) studied visual search using arrays containing fewer than 8 elements. They found parallel set-size functions for positive and negative responses rather than the 2:1 ratio expected in a serial exhaustive search. Pashler felt his results suggested at least a partial parallel search of four or five elements at a time followed by a serial identification stage. Models of this sort have been developed by Pashler (1987) and Duncan & Humphreys (1989) and have proven successful in accounting for several aspects of search data.

Finally, extensive practice alters set-size effects. The data shown earlier in Figure 3 were obtained by Steinman (1987) after his subjects had practiced for only about 200 trials. The same subjects were then given extensive additional practice for about 10,000 trials. Gradually the set-size effect for conjunction targets disappeared and the search function became flat. It was as if with sufficient practice the search for a conjunction target became a parallel search process—i.e. as if the conjunction were eventually processed "pre-attentively," "without attention," or "automatically."

The circumstances under which extensive practice leads to perceptual automaticity have been systematically investigated by a number of psychologists (e.g. LaBerge 1975; Shiffrin & Schneider 1977; Schneider et al 1984; and Logan 1988). For example, Shiffrin & Schneider found that visual search for a target letter among distractors changes character with extensive practice, so long as the letter is always a target ("constant mapping"), rather than sometimes a target and sometimes a distractor ("varied mapping"). Not only does such extensive practice lead to a performance without any evidence of processing tradeoffs, but also the processing seems to occur almost involuntarily—that is, you perceive it whether you wish to or not. For example, as a highly practiced reader of English you are unable to look at the word "DOG" without rapidly activating or retrieving both phonetic and semantic knowledge consistently associated with the word (which would not be true if you had only learned to read Arabic).

DIRECTING COVERT VISUAL ATTENTION

While one has considerable flexibility in allocating or directing covert attention, there are limits. First of all there are limits to how precisely one can focus attention on specific sources to the total exclusion of others. Second, it takes time to shift from one allocation to another (switch attention). This section of the paper considers several representative lines of research bearing on these issues.

Focusing Visual Attention

Early in the study of attention it became clear that one could not always focus attention on one source to the exclusion of others. For example, while trying to listen exclusively to one of two voices in dichotic listening tasks, subjects often reported hearing highly familiar words such as their own names spoken by the "ignored" voice (Moray 1959). It was as if the processing of such highly familiar and normally relevant words was so automatic that they were processed involuntary, without attention.

Such failures of focal attention led some investigators to argue that selective (attentional) mechanisms operate much later in the perceptual process than simple "sensory filters" (e.g. Deutsch & Deutsch 1963; Treisman 1969). The idea is that selection operates on representations (e.g. semantic) activated relatively late in the perceptual process. The primary evidence for this late selection view are Stroop-like interference effects where one seems unable to ignore certain stimuli. For example, failures of focal attention have been demonstrated in visual letter-detection tasks where subjects sometimes seem unable to ignore letters adjacent to a target letter (Eriksen & Eriksen 1974; Eriksen & Schultz 1979). These adjacent "flanking" letters can reduce the time to respond to the target if they are associated with the same response, or lengthen response times if they are associated with a different response. Murphy & Eriksen (1987) found such interference occurred only if the flanking letters were within about a 1° visual angle of the target letter, so long as the subject knew exactly where the target would occur. If, on the other hand, the subject was uncertain about target location, interference from flankers up to 2–3° from the target could occur. This led Eriksen to liken attention to the field of a "zoom-lens": To monitor a wide area the lens widens its field, leading to flanker effects; but when a target can occur in only one place, the lens zooms in on that location, largely eliminating flanker effects. Recently Yantis & Johnston (1990) developed procedures that seem optimally to cue subjects concerning target position and virtually eliminate flanker effects. LaBerge et al (1991) developed another procedure for eliminating flanker effects. They presented a digit at the target location just before the target and flankers were presented. Subjects were to respond to the target only if the preceding digit was a seven. As recognition of the digit was made more difficult (by shortening its duration from 250 to 50 ms) flanker effects gradually disappeared (as if the increased difficulty of processing the digit prevented processing of the flankers). The preceding results are consistent with the recent proposals of Lavie & Tsal (unpublished), who argue that early selection (effective focal attention) occurs only if the processing load is sufficiently high to preclude the incidental processing of irrelevant stimuli. Furthermore, the relevant stimuli must be clearly discriminable from irrelevant stimuli. They present a series of experiments in which perceptual load and discriminability influenced the success of focal attention as their theory would predict.

Thus under certain conditions it seems attention can be allocated to a small region, with little processing of some stimulus events outside that region. It also seems clear that one can allocate attention over a wider area, perhaps the whole visual field (Eriksen 1990). If visual attention is like a spotlight (Posner 1980), that spotlight has a variable diameter (see Eriksen & St. James 1986, 1989; Eriksen & Yeh 1985; LaBerge & Brown 1986, 1989). Other aspects of the spotlight metaphor must also be clarified. For example, it has been argued that sensitivity to stimuli seems to fall off slowly at the edge of the area attended to—a gradient of attention (Eriksen & St. James 1986; Downing & Pinker 1985). Also, while the previously cited studies indicate one can eliminate flanker effects under certain circumstances, other sorts of peripheral stimuli, such as motion or a brief flash, seem to command attention automatically (Miller 1989; Kröse & Julesz 1990; Müller & Rabbit 1989; Tipper et al 1990).

Switching Attention

The most widely used method for inducing a shift in visual attention is to pre-cue a subject concerning the likely location of a subsequent target. If the time between cue and target is sufficiently short, subjects don't have time to move their eyes, and any enhancement of processing at the target location can be attributed to a covert shift in attention induced by the cue (assuming that any general alerting or warning effect of the cue is assessed by occasionally presenting a positionally neutral version of the cue as a control condition; see Remington & Pierce 1984). After over 20 years of research on the effect of pre-cuing, Eriksen (1990) concluded that an enhancement of processing at the cued location (a reduction in response time, or an increase in accuracy) begins within 50 msec of a cue and continues to grow until it reaches asymptote about 200 msec after the cue—i.e. there doesn't appear to be an abrupt, all-or-none switching but instead a gradual buildup of "attention" at the cued location, which reaches a peak after about 200 msec. In terms of the spotlight metaphor, it is as if the spotlight went off at one point and then gradually came on again at the target location. This can be contrasted with a continuously illuminated spotlight that illuminates intervening points while moving in analog fashion from one point in the visual field to another. Data that seemed to support the analog view had been presented much earlier by Shulman et al (1979) and Tsal (1983). However, rather telling critiques of the earlier interpretations of those data have recently been presented by Yantis (1988) and Eriksen (1990). Furthermore, a study by Eriksen & Webb (1989) failed to show a relation between time to shift attention and distance between elements to be attended.

The idea that it takes time to switch or shift one's allocation of attention goes back at least to the beginning of experimental psychology and the so called "complication clock experiment" in which subjects tried to report where a moving clock hand was positioned when a bell sounded. Subjects tended to report the hand as further along than it really was. This phenomenon was attributed to the time it took to "switch attention" from "listening for the bell" to "seeing the clock." Sperling & Reeves (1980) employed a more sophisticated but conceptionally similar approach to measuring attention switching. Their subjects fixated on a stream of successively superimposed digits while attending to an adjacent stream of letters. When a subject detected a target letter C in the letter stream she was to switch her attention immediately to the fixated digit stream and report the first digit she saw. Subjects typically reported a digit that occurred 300–400 msec after the target, independently of the rate at which the digits were presented. Note that this "attention reaction time" ostensibly includes the time to recognize the target letter, as well as the time to switch attention, and the two are hard to separate.

More recently, Weichselgartner & Sperling (1987) employed a variant of this task. Subjects fixated on a digit stream until they saw a square appear around a digit. They were then to report the digit within the square, as well as the subsequent three digits. Based on both subjects' subjective statements and the bimodal nature of the digits reported, the authors identified two processes: an automatic process consisting of a rapid, effortless, "first glimpse" of the digit within the square; and a controlled process producing a slower, effortful, "second glimpse" of digits occurring more than 200 or 300 msec after the square.

The idea that both automatic and controlled processes mediate shifts in attention is suggested by other research as well. As noted earlier, visually pre-cuing a subject to direct attention to particular parts of a visual array produces substantial shifts of attention within as little as 50 msec of cue onset (see Eriksen 1990). However, some cues seem to induce shifts of attention more rapidly than others, the most effective being cues at or near locations to which attention is to be directed. Cues such as a centrally located number indicating that attention should be shifted to a specific peripheral region induce much slower shifts (see Yantis & Jonides 1990).

This and other evidence has led a number of investigators to postulate two types of attention shifts. For example, Mackeben & Nakayama (1987; see also Nakayama & Mackeben 1989) argued that there are both sustained and transient components of visual attention. The sustained component is maintained through effortful control and is shifted more slowly than the transient component, which is automatically evoked by the cue. Müller & Rabbitt (1989) told subjects to allocate visual attention on the basis of a centrally located arrow and to ignore briefly brightened squares that occasionally came on prior to the test stimulus. In spite of these instructions subjects revealed an increased sensitivity to targets presented within a brightened square. The experimenters concluded that attention allocation based on the fixated arrow was a controlled process while that evoked by the peripheral squares was essentially an automatic capture of attention. Kröse & Julesz (1990) similarly concluded that visual cues presented in the same position as a subsequent target produce a fast, automatic, "bottom-up" control of attention that can be distinguished from a slower, voluntary, "top-down" mode of control.

DISTINGUISHING ALLOCATION AND DECISION-MAKING

Faster responding to targets at pre-cued locations doesn't necessarily imply enhanced information processing. Faster responding may reflect more liberal decision-making. Shaw (1984) in fact concluded that pre-cuing effects in luminance detection reflected only changes in decision criteria (see also Sperling & Dosher 1986). However, Shaw did find evidence of an "attentional" (quality of processing) effect in letter identification. One problem with this distinction should be noted. If luminance increments are more likely to occur at pre-cued locations, the cue carries information concerning the appropriate response ("increment"/"no increment"). In contrast, the cue in a letter identification task need not carry the same sort of information. For example, suppose a subject were asked to decide whether a briefly presented letter was an F or a K. A pre-cue could indicate the most likely location for the letter to occur without indicating anything about which letter is more likely. Thus the difference between luminance detection and letter identification may be confounded with the difference in correlation between location and response. Furthermore, even if a cue doesn't indicate which response is more likely, it can indicate which areas of an array should be given more weight when the decision process involves a weighted integration of impressions (Kinchla 1980).

In the last few years several studies have been designed to separately assess the effects of pre-cues on "decision-making" and "quality of processing" (Downing 1988; Müller & Findlay 1987; and Müller & Humphreys 1991). Each used an approach based on Signal Detection Theory (Green & Swets 1966) whereby shifts in decision-making are indicated by estimates of β, the decision criterion, and shifts in the quality of processing by d', the sensitivity measure.

Downing (1988) had subjects maintain central fixation while monitoring a circular array of 12 small squares in which targets could occur. Each trial began with either an arrow cue indicating a specific square or a circle cue indicating all 12 squares. A stimulus pattern was then presented consisting of targets shown at from 0–4 of the square locations. Four locations were then successively indicated by a probe stimulus. During each probe the subject used a four-valued rating scale to indicate how confident he was that a target had just occurred in the probed location. If a location was pre-cued with an arrow, a target occurred in it with probability .8, and the position was always probed. Otherwise all the probed locations were selected quasi-randomly on each trial, and a target occurred in each with probability .5. The nature of these targets depended on the task. In a luminance-detection task the target was a luminance increment and nontargets no change in luminance. In three discrimination tasks targets were either a luminance increment, a vertical line, or two perpendicular lines, while the nontargets were, respectively, a luminance decrement, a horizontal line, or two parallel lines. Downing found enhanced processing (larger d' estimates) at the arrow-cued location in all four tasks, with progressively poorer processing at other probed locations as their distance from the cued location increased. Subjects were also more liberal in reporting targets (lower d') at the cued location. While it is not clear how powerful her tests were, Downing found no evidence of an order of report effect, nor any dependence among the four responses on each trial.

While Downing's study is impressive, it does involve a rather complex paradigm in which subjects must retain information about the sensory events evoked at many locations until the end of the probe sequence. One could argue that subjects might immediately code the sensory event at an arrow-cued location into one of the rating responses, since that location was always probed, then code the information in the other locations less carefully into a less precise code. A similar proposal was made by Duncan & Humphreys (1989), except they suggest that it is simply the order of encoding from a rapidly decaying iconic store that determines the information lost from each location. In any case, if sensory information were differentially lost during these initial encodings, rather than during the probe sequence, Downing's test for order of report would not reveal it. Such an encoding enhancement of d' at the pre-cued location would not reflect a difference in the initial quality of information, but simply a differential encoding of sensory information because of the need to retain it during the long probe sequence. (Downing acknowledges this possibility but asserts it would simply be another aspect of attention.) Finally, since there were so many (12) locations to monitor, subjects might mistakenly attribute a strong sensory impression of a target to the wrong location, thereby inflating estimates of false-alarm rates.

In an attempt to avoid some of these issues Hawkins et al (1990) conducted a similar study using a simplified detection paradigm. Their subjects monitored four locations for the occurrence of a target (a luminance increment). Each trial began with a pre-cue indicating one of the four locations, or all four. (This pre-cue occurred either near fixation or near the cued locations.) Following the pre-cue a target occurred at one of the four locations or at none of them. This was followed by a half-second mask and finally a single probe indicating that the subject should rate his confidence that a target had been presented in the probed location. If a single location was pre-cued it was probed with probability .76, otherwise one of the other locations was equally likely (.8) to be probed. If all four locations had been pre-cued, each was equally likely (.25) to be the one probed. In all cases, a target was presented in the probed location with probability .5. As in the Downing study, the results were seen as indicating an enhanced quality of processing (d') at the cued location (for both central and peripheral cuing).

While this study involved a simpler paradigm than Downing's, it too required subjects to retain sensory information from four locations until a probe is presented (after the half-second mask). Thus here again subjects might more carefully or quickly encode the sensory information evoked at the single pre-cued location, since it was most likely to be probed. There are also significant correlations among pre-cued, probed, and target locations. For example, when only one location was pre-cued it had a .76 × .05, or .34 probability of containing a target on that trial, and each of the other three locations a probability of (1 − .76) × .33 × .5, or .04. However as soon as a location was probed it had a .5 probability of having contained a target. These complex correlations among events at the four locations are a form of redundancy that the subject might use in determining a response.

Recently Juola et al (1991) conducted a series of experiments designed to evaluate variants of the "attentional spotlight" idea. Their subjects viewed briefly presented (150 msec) arrays of 12 letters arranged such that four letters fell within each of three concentric rings—an inner ring, a middle ring, and an outer ring (none of the letters was at a more than 3-degree visual angle from a central fixation point). On each test trial 11 of the 12 letters were distractor Xs while the other target letter was either an L or an R. The subjects' task was to identify this target letter. Of principle interest was the effect of pre-cuing the subject concerning which ring was most likely to contain the target with the cue valid on 80% of the trials. The results indicated subjects were both faster and more accurate in identifying targets in the cued ring.

Juola and his colleagues used these data to evaluate three models: one considering attention as analogous to a variable-diameter spotlight (the "zoom lens" model); one in which attention was likened to a narrowly focused spotlight that serially scanned the letters; and one in which attention could be allocated to any one of the three rings. They concluded that this later model provided the best account of the data; e.g. attention could be allocated in an O-shaped pattern to include only the outer, or the middle, ring.

The problem with this conclusion is that Joula et al only consider models in which the "quality" of information processing differed in the cued and non-cued regions. They failed to consider models in which the cue effects were mediated solely by decision processes. For example, suppose the quality of processing was the same in cued and noncued regions but *the subject simply give more weight or credence to the information extracted from the cued region*. On a particular trial, he might be fairly sure he saw an L in the outer ring, and also feel he saw a K in the middle ring. He might resolve these conflicting impressions by giving more weight to his impression of the outer ring if it had been cued on that trial. Since the cues were valid on 80% of the trials, this *weighted integration of information* could account for the faster and more accurate responses to targets in cued regions and there wouldn't be a simple speed-accuracy trade-off. Note that this interpretation could be tested experimentally by presenting cues after the letter array but before the response. A similar pattern of results would support the view that the cues influenced decision-making rather than the initial processing of visual information. Unfortunately this was not done in the Juola et al study, so their data are inconclusive. A more extensive and formal development of the weighted-integration idea applied to the detection of target letters in multi-letter displays is presented in Kinchla (1977).

EXPECTANCY AND PRIMING AS ATTENTIONAL PROCESSES

Much of the work we have considered to this point has involved cuing a subject about where a stimulus is most likely to occur. Enhanced processing at that location and poorer processing at other locations have been interpreted as being due to a spatial allocation of attention. Similar processing tradeoffs can be produced by cuing a subject about the type of stimulus most likely to occur, rather than about where it will occur. This procedure often leads to enhanced processing of the anticipated stimulus and poorer processing of less likely stimuli. Such a processing tradeoff is often interpreted in terms of the subject's "preparation" or "set." This view goes back at least to William James, who wrote:

> The effort to attend . . . consists in nothing more nor less than the effort to form as clear an IDEA as is possible of what is there portrayed. The idea is to come to the help of the sensation and make it more distinct (James 1904:239).

Pre-cuing the "idea" of the stimulus facilitated its subsequent recognition, a process James referred to as "preperception."

More specific theories of how one prepares to process specific stimuli have been developed to account for data from choice–reaction time studies. For example, Falmange & Theios (1969) developed a model in which subjects processed a test stimulus by sequentially comparing it to a "stack" of stimuli held in memory. Cuing a subject to anticipate a particular stimulus caused it to be placed near the top of the stack. This sort of preparation produced faster responses to likely stimuli and slower ones to unlikely stimuli. There are also many other ways of explaining the effects of a priori stimulus probabilities in choice–reaction time tasks, including shifts in decision criteria and muscle preparation for a particular response (see Luce 1986 for a review of such theories). However, there do seem to be tasks in which the subject actually prepares to process a particular type of stimulus. For example, Figure 6 presents four stimulus patterns composed of Xs and Os, which are susceptible to alternative figure-ground organization. The top two patterns define the large letters L and H if the Os are seen as "figure" against a "ground" of Xs, while seeing the same large letters requires the opposite organization in the lower two patterns. Leading a subject to anticipate one type of organization speeds recognition of large letters defined in that fashion and slows recognition when the less likely organization is required. The fact that this tradeoff in

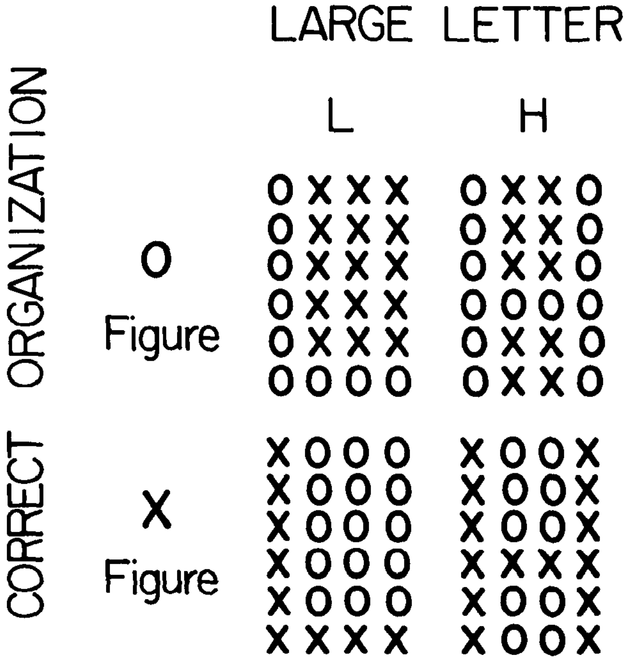

Figure 6 Four stimulus patterns employed by Kinchla (1974) susceptible to alternate figure-ground organization: Xs as figure and Os as ground (top two patterns), or vice versa (bottom two). If subjects are prepared to make the correct organization they identify the large letter about one half second faster than if they are prepared to make the wrong organisation.

reaction time is linear is consistent with a mixture of fast responses when the subject's initial organization is correct and slow responses when it isn't (Kinchla 1974).

Certain ideas about "filters" that enhance processing of relevant stimuli and inhibit processing of irrelevant ones can be interpreted as preparation for specific types of stimuli (rather than a spatial allocation of attention). It is also possible to view such effects as an allocation of attention to specific channels or sensory modalities. For example, Shulman & Wilson (1987) had subjects view large letters made up of smaller ones. Their detection of high-frequency gratings was enhanced while the subjects tried to identify the smaller letters, and their detection of low-frequency gratings was enhanced while they tried to identify the larger one. It was as if they could alternatively "filter" or enhance high or low spatial frequency channels, much as one might attend to high- or low-frequency components of a sound (see Green & Swets 1966).

Viewing the matter in the broadest way one could argue that the recent priming or activation of any sort of knowledge makes it more accessible and therefore more influential in processing new stimuli. This knowledge becomes James's "preperceptive idea," which enhances the processing of related stimuli. In recent years a number of studies have shown how a prior stimulus ("prime") can enhance the processing of subsequent stimuli—for example, speeding such processes as lexical decision-making or completing fragments of words and pictures (see Richardson-Klavehn & Bjork 1988 for a review of such work). Thus either explicitly cuing a subject to expect a particular type of stimulus or implicitly priming related knowledge may lead to enhanced processing of the expected or primed class of stimuli; the processing of unexpected or unprimed classes is slower. In fact there is even evidence of a sort of negative priming. Tipper & Driver (1988) presented subjects with a series of overlapping red and green forms, with instructions to identify forms of one color while ignoring those of the other color. They found that if a specific form was the to-be-ignored color on one trial and the to-be-identified color on the next trial, the identification response was slowed. It was as if the form's appearance in the to-be-ignored color had produced a sort of negative priming, an inhibition of the form's identification on the next trial. It would thus seem that preparation based on expectancy or priming is another form of attending; it involves processing tradeoffs that enhance the processing of some stimuli while reducing that of others.

NEUROLOGICAL STUDIES OF ATTENTION

While an extensive review of neurological studies of attention is beyond the scope of this paper it seems useful to mention some of the more promising lines of research.

Basically there are four major pathways for visual information. Two of these, the geniculostriate and tectopulvinar pathways, carry visual information from the eye to visual areas in the occipital lobe of the cortex. From these areas information is carried to other visual areas in the parietal lobe via a dorsal or occipitoparietal pathway, and to the temporal lobe via a ventral or occipitotemporal pathway. Visual areas in the temporal lobe seem to be primarily engaged in processing spatial location and movement, and those in the temporal lobe with pattern recognition and color. (These functional differences can to some degree be traced all the way back to the retina in terms of the types of retinal ganglion cells, magnocells, and parvocells, feeding into the higher systems.) The dorsal and ventral cortical "pathways" are actually composed of many different visual areas with many reciprocal interconnections. The organization of these areas seems to be hierarchical, as evidenced by the progressive latency of evoked neuronal responses and the progressively larger receptive fields (for reviews of these neural systems see DeYoe & Van Essen 1988; Desimone & Ungerleider 1989; and Maunsell & Newsome 1987).

Following the seminal work of Wurtz & Albano (1980) many studies have focused on what might be termed the cognitive aspects of stimulus-evoked activity in the visual system; they have shown that such neural activity depends on more than the physical properties of the evoking stimulus. For example, light-evoked (event-related) potentials in visual cortex are larger if the subject is pre-cued to expect a stimulus at the location where it occurred, rather than some other location (Hillyard & Hansen 1986).

Cognitive aspects of receptive fields have also been identified. Moran & Desimone (1985) trained monkeys to respond to one or the other of two visual stimuli within the receptive field of a cell in visual area V4. The currently relevant stimulus was indicated by a cue. If this currently relevant stimulus had not previously been effective in evoking a response while the other stimulus had, the response occurred as before. However, if the relevant stimulus had not previously evoked a response while the other stimulus had, the cell's response was highly attenuated (even though the previously effective but nonrelevant stimulus was present in the cell's original receptive field). It was as if the cell's receptive field had contracted to include only the relevant stimulus. This relevance effect occurred only when both stimuli fell within the cell's original receptive field. If one of the stimuli fell outside the field, relevance had no effect on the cell's response. While these effects were not found in V1 or V2 cells, similar results were obtained with cells in the monkey's inferior temporal cortex, although the receptive fields of these cells were so large that both stimuli were always within the field. Moran & Desimone interpreted their results as reflecting an "attentional" process beginning in V4 that contracted a receptive field around the "attended to" (relevant) stimulus whenever two or more stimuli fell within the cell's original field (with a finer spatial tuning of this process in V4 cells than in inferior temporal cells).

Just as the sizes of receptive fields have been shown to contract about critical stimuli, tuning curves for both color- and orientation-sensitive cells in V4 have been shown to contract or sharpen when an animal's task requires a finer discrimination of those dimensions. It is as if the animal is "attending more closely" to that dimension (Spitzer et al 1988; Spitzer & Richmond 1990).

While the contraction of receptive fields and the sharpening of tuning curves would seem to serve a selective or "attentional" function, where does the control of such processes reside? A number of investigators have concluded that the pulvinar nucleus of the thalamus serves such a function (e.g. Crick 1984; LaBerge & Buchsbaum 1990; and Posner & Petersen 1990). It seems a likely candidate because it has reciprocal connections with areas throughout the occipitotemporal system (Ungerleider et al 1983), and patients with pulvinar lesions exhibit deficits in directing visual attention (Rafal & Posner 1987). The pulvinar nucleus also exhibits increased blood flow in PET scans when subjects are asked to ignore a particular stimulus, as if it were engaged in filtering out that stimulus. (LaBerge & Buchsbaum 1990).

Desimone et al (1991) examined the role of the pulvinar nucleus by first training a monkey to respond on the basis of one visual stimulus while ignoring a second stimulus in the opposite visual field. They then chemically disabled the monkey's lateral pulvinar nucleus and found the monkey had great difficulty in ignoring a distractor in the affected (contralateral) field when the target was located in the other (normal) field. However, only when there was a competing stimulus present did deactivation of the pulvinar nucleus produce performance deficits. Thus Desimone et al concluded that the deactivated nucleus interfered with the same sort of attentional gating they had observed in inferior temporal cells whenever two stimuli were presented simultaneously.

Other cortical areas involved in oculomoter control have, not surprisingly, been implicated in the control of covert spatial attention (attending without eye movements). These include, in addition to the pulvinar nucleus, the posterior parietal cortex and the superior colliculus. (See Goldberg & Colby 1989 for a review of this work.) Some of the evidence implicating these areas is clinical. Posner & Petersen (1990) assert that while patients with damage to any of these show deficits in shifting visual attention there are subtle differences among these deficits. Damage to the posterior parietal lobe reduces the patient's ability to disengage from an existing focus of attention so as to shift that focus to a position opposite to the side of the lesion. In contrast, lesions to the superior colliculus show shifts whether or not attention was initially focused. Thalamic (pulvinar) lesions seem to reduce the patient's ability to maintain focused attention. It is as if "The parietal lobe first disengages attention from its present focus, then the midbrain area acts to move the index of attention to the area of the target, and the pulvinar is involved with reading out data from the indexed locations" (Posner & Petersen 1990:28).

Other areas in the associative cortex undoubtedly serve selective or attentional functions that are slowly being revealed by PET studies of blood flow during various cognitive tasks (see LaBerge & Buchsbaum 1990; Posner & Petersen 1990; Petersen et al 1988)—for example, the type of cognitive task discussed earlier, in which a word can prime or activate semantic knowledge that then facilitates or enhances the subsequent processing of semantically related words.

DISCUSSION

Discoveries in neuroscience are at last identifying neural systems that underlie attentional processes studied at the behavioral level. In a much earlier review of work on attention I argued that "Attention should not be thought of as a single entity. It seems more useful to assume that a variety of cognitive mechanisms mediate selectivity in information processing" (Kinchla 1980:214). More recently, in his excellent review of work on attention in the *Annual Review of Neuroscience*, Posner concluded that research "suggests to us a possible hierarchy of attention systems,. . . . [It] involves the operation of a separate set of neural areas whose interaction with domain specific systems (e.g. visual word form or semantic association) is the proper subject for empirical investigation" (Posner & Petersen 1990:34, 39).

Neural centers in the tectum and hypothalamus seem to modulate specific components of incoming sensory information, providing the sort of filtering of irrelevant information and enhancement of relevant information that theories based or purely behavioral evidence have long suggested. These effects are apparent in the cognitive aspects of cortical receptive fields described earlier (e.g. Desimone et al 1991; Spitzer & Richmond 1990). Other attentional centers involved in higher-order modes of selection such as semantic priming are being identified through altered patterns of cerebral blood flow during various cognitive tasks (e.g. LaBerge & Buchsbaum 1990; Posner & Petersen 1990).

This review has dealt primarily with behavioral research, especially that on visual search, and the directing of visual attention. A number of general comments may be made about each.

Visual Search

Some search studies attempt to limit the role of overt eye movements by using tachistoscopic presentation or instructing subjects to hold their eyes still (e.g. Enns & Rensink 1992); other studies place no constraints on eye movements (e.g. Treisman & Sato 1990). Most of the data supporting Treisman's feature-integration theory or its alternatives were collected with no constraints on eye movements. Since these studies often involved response times as long as 1 or 2 sec, subjects had ample time to make several eye movements. Little research has been done on the role of such eye movements. This is surprising because questions about the "serial" versus "parallel" nature of the search process are ubiquitous in the literature. If, for example, perceiving the details or colors defining a target required direct fixation (foveal processing), the search process would necessarily be serial as the subject shifted fixation from one array element to the next. Even if the situation were less extreme so that target processing were simply enhanced on the fovea, the interplay of overt and covert shifts of attention should be complex. It seems particularly relevant to assess the degree to which foveation facilitates the processing of targets, or to use smaller stimulus arrays that can be presented so briefly that eye movements can't occur.

In most of the search literature reaction time is the most frequently used independent variable. Subjects are normally requested to "respond as rapidly as possible while avoiding errors" (Cavanagh et al 1990). A problem with this strategy is that it leads subjects to perform at a point on the speed/accuracy–tradeoff function where small shifts in error rates (e.g. 1%–2%) may be associated with large shifts in mean reaction time (see Luce 1986). Such small shifts in error rates are unlikely to be statistically significant given the typical amount of data collected in these studies. Thus experimenters often conclude that shifts in mean reaction times are not due to speed/accuracy tradeoffs if the independent variable has no significant effect on error. This is clearly inappropriate since one doesn't prove the null-hypothesis; nonsignificance simply means there is insufficient evidence to reject it. It would seem useful actually to trace out some of the speed/accuracy functions for search paradigms of this sort (see Luce 1986).

Other questions regarding visual search were raised earlier in the paper: Are small arrays ($n < 8$) searched in the same way as larger ones (see Pashler 1987)? Can extensive practice gradually flatten search functions (see Steinman 1987)?

Directing Attention

The balance of evidence at this point seems to support the idea that subjects can rapidly switch attention on the basis of a pre-cue so as to enhance the processing of stimuli at the cued location. Analyses of data from several studies using the signal detection measures d' and β has supported this view: The cues apparently influenced both d' and β. Nevertheless, the studies involve complex paradigms in which subjects are required to maintain considerable sensory information until a response is called for or probed. Thus critics can question whether the sensory information initially available at the cued location was actually enhanced, or whether it was preferentially encoded into a form better suited for retention until the probe.

It should also be noted that the apparently separate assessment of "sensitivity" by d' and of "response criterion" by β may be misleading. For example, it is conventional to treat β as constant during a long series of detection trials. Suppose it were actually a Gaussian random variable. Then the conventional measure of β would be an estimate of its expected value, and its variance would influence d'. In other words, variability in a subject's decision criterion (a parameter of the decision process) would be represented in d', the sensitivity measure (see Green & Swets 1966). If pre-cuing a location could evoke a more stable (less variable) decision criterion for that location it would have the same effect on d' as reducing sensory "noise." Thus interpretation of pre-cue effects as influencing "sensory" versus "decision-making" processes requires caution.

Evidence is also accumulating that there are at least two forms of attention: cuing: a rapid, to some degree involuntary, automatic, switching; and a slower, more controlled form of switching. Cues such as sudden light onsets or motion near the cued location seem most likely to induce the automatic form of attention switching.

Another type of attention switching would seem to be involved in the "preparation" one sometimes seems to make to enhance the processing of a particular type of stimulus. For example, suppose you were asked to process rapidly the type of patterns shown in Figure 6. Before the pattern was presented you might alternatively be prepared to organize the Xs as "figure" and the Os as "ground," or vice versa. Data I have collected (R. Kinchla, unpublished observations) indicates that something like this occurs, and that it takes about one half a second to switch from one form of preparation to the other.

"Priming" a subject so as to "activate" certain knowledge in memory (make it more accessible or salient) seems to enhance the subject's ability to process related stimuli (compared to other, nonprimed stimuli). Thus priming seems to be a way of allocating attention. If one could assess the time required to "deactivate" or "unprime" knowledge and prime or activate other knowledge it would represent the time required to switch to another form of attention. In fact, it may be a special case of the rather lengthy and difficult process whereby one switches from performing one type of complex cognitive task (calculating on your income tax) to another (writing a poem). There is clearly a considerable startup period during which knowledge required to work on each task is progressively "primed" or "activated." This is why it is much more efficient to work on one task for a long time, or to completion, than it is to switch back and forth between two tasks.

In conclusion, then, it appears there are many mechanisms that mediate selectivity in human cognition, ranging from systems that alter the early flow of sensory input to higher-order associative processes that prime or activate knowledge and thereby enhance subsequent processing.

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