# Feature Analysis in Early Vision: Evidence From Search Asymmetries

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In this article we review some new evidence relating to early visual processing and propose an explanatory framework. A series of search experiments tested detection of targets distinguished from the distractors by differences on a single dimension. Our aim was to use the pattern of search latencies to infer which features are coded automatically in early vision. For each of 12 different dimensions, one or more pairs of contrasting stimuli were tested. Each member of a pair played the role of target in one condition and the role of distractor in the other condition. Many pairs gave rise to a marked asymmetry in search latencies, such that one stimulus in the pair was detected either through parallel processing or with small increases in latency as display size increased, whereas the other gave search functions that increased much more steeply. Targets defined by larger values on the quantitative dimensions of length, number, and contrast, by line curvature, by misaligned orientation, and by values that deviated from a standard or prototypical color or shape were detected easily, whereas targets defined by smaller values on the quantitative dimensions, by straightness, by frame-aligned orientation, and by prototypical colors or shapes required slow and apparently serial search. These values appear to be coded by default, as the absence of the contrasting values. We found no feature of line arrangements that allowed automatic, preattentive detection; nor did connectedness or containment—the two examples of topological features that we tested. We interpret the results as evidence that focused attention to single items or to groups is required to reduce background activity when the Weber fraction distinguishing the pooled feature activity with displays containing a target and with displays containing only distractors is too small to allow reliable discrimination.

Vision provides an organized representation of the world around us, including objects and organisms located or moving on a structured ground. Much of what we see is recognized and labeled, but this is not essential to vision. Unless basic cues (e.g., to solidity) are completely misleading, people can maneuver successfully in an unfamiliar environment. They can reach for, grasp, and manipulate objects never previously encountered. Marr (1982) distinguished the goal of early vision—to form a description of the three-dimensional surfaces around us—from that of later vision—to identify or recognize objects and their settings. Most theorists agree that the early description derives from spatial groupings of a small set of simple primitives that are registered in parallel across the visual field. These primitives, or functional features, need not correspond to simple physical dimensions like wavelength or intensity. On the contrary, their function should be to provide an "alphabet soup of descriptive chunks that are almost certain to have some fairly direct semantic interpretation" (Witkin & Tenenbaum, 1983, p. 509). Examples (according to these authors) might be "coherent regions, edges, symmetries, repetitions, smooth gradients,

flow patterns" (Witkin & Tenenbaum, 1983, p. 513). Thus we expect the visual system to be sensitive to simple regularities in elements of different reflectance, color, and texture.

Physiologists are discovering an increasing number of specialized visual areas, or maps, "at a rate of about one every two years" (Cowey, 1985, p. 46). These areas contain cells that are more sensitive to variations in some properties than in others. Different areas, or different orthogonal organizations within areas (e.g., within column vs. between column groupings—Hubel & Wiesel, 1977, Maffei & Fiorentini 1977; or laminar segregation—Dow, 1974), appear to code differences in orientation, size or spatial frequency, stereoscopic depth, color, and directions of movement (Cowey, 1979, 1985; Zeki, 1978, 1981). It is tempting to suppose that these modular subsystems are concerned with extracting the functional primitives of early vision (although we make no assumption that any single cell can be equated with a single functional feature detector). Both computational arguments and physiological evidence converge, then, on the idea that some analysis or decomposition of visual stimuli is likely to occur.

In this article we are concerned with the nature of the functional features coded by the visual system. We review some behavioral findings using a new diagnostic to identify separable values on different dimensions of perceptual analysis, and we propose a theoretical framework in which the results may be interpreted.

The quest for behavioral tests to define a limited vocabulary of primitive features has tempted many psychologists. The fruits of this research show some encouraging convergence on possible candidates, but they also show some disagreement as well as both empirical and conceptual confusion (see Treisman, 1986, for a general review). It is useful to draw some general

distinctions, first between different forms of analysis and then between different levels of representation.

## Feature Analysis: Some Logical Distinctions

### Parts and Properties

Two kinds of decomposition into more primitive elements are possible: analysis into properties and analysis into parts. The visual system may respond separately to values on different dimensions of a single stimulus, for example, the stimulus' color, size, orientation, or direction of movement; or it may respond separately to different component parts, for example, a vertical line or an intersecting curve in a two-dimensional shape, or a flat surface or cylindrical legs in a three-dimensional object.

These two forms of analysis are orthogonal, because each local part must have at least a minimal set of properties. The bars and blobs of Marr's (1982) primal sketch and the "textons" of Julesz's (1984) texture-segregation theory are local elements or parts of the image; each has a particular conjunction of values on a number of different dimensions (brightness, color, orientation, size, or spatial frequency). On the other hand, the intrinsic images of Barrow and Tenenbaum (1978) each encode a different dimension of variation (orientation, reflectance, distance, etc.) in a separate topographic representation. Operations of grouping to define global objects with internal structured relations (Beck, Prazdny, & Rosenfeld, 1983) apply only to local elements or parts, although the choice of which elements to group is strongly constrained by similar properties and by spatial proximity.

In this article we are concerned with dimensional analysis, with properties rather than parts. We define a *dimension* as a set of mutually exclusive values for any single stimulus (Garner, 1974; Treisman, 1986). Whereas a line can be both red and vertical (values on different dimensions), it cannot be both vertical and horizontal (values on the same dimension). We will use the word *feature* to refer to a value on a dimension if (a) that dimension appears to be perceptually coded as a distinct and separable entity and (b) the value on that dimension is coded independently of any other values on the same dimension that are also present in the field. In this article we will be concerned primarily with evidence for separability of features *within* a dimension rather than with separability of one dimension from another.

Separability is a relation between features rather than an absolute property of an individual feature. Thus a particular red may be coded independently of green and function as a separable feature in a display containing only red and green. Yet it may activate largely overlapping detectors with a closely neighboring pink, so that in a display containing both the red and the pink, the red will no longer count as a separable feature. A feature in our sense is similar to the concept of a neural "channel" (Braddick, Campbell, & Atkinson, 1978; Graham, 1980; Wilson & Bergen, 1979). However, we do not assume that the channels are necessarily discrete, each centered on a particular absolute value. Some, perhaps most, dimensions may constitute a continuous array of feature detectors, each with a certain bandwidth of response on the dimension in question. Different detectors may respond to overlapping distributions of values. A particular pair of stimuli in a particular display would be said

to activate separable feature detectors if their values were sufficiently distinct for the responses to appear in nonoverlapping sets of detectors.

### Levels of Processing

It is common to distinguish two or more intermediate mappings on two or more different parallel paths, which transform the visual input into a description of the perceptual world. Each representation is defined by a different vocabulary of functional elements (whether parts or properties) extracted at that level, together with some specification of the spatial and structural relations between them. Thus image dimensions, such as intensities, wavelengths, retinal locations, and binocular disparites, are coded at one level, then combined and transformed to define at another level the dimensions of real-world objects and surfaces, such as reflectances, surface colors, distances, and locations in three-dimensional space. Early segregation and grouping may depend on one set of elements, and a new vocabulary of elements, specialized for the purpose, may be recruited to describe objects rather than local surfaces and edges (Hughes, 1982; Pomerantz, 1981). Examples for objects might be the components segmented by minima of curvature (Hoffman & Richards, 1985) or sets of independently defined volumetric primitives such as generalized cones (Marr & Nishihara, 1978) or the more elaborate vocabulary of parts, or "geons," proposed by Biederman (1985). In Marr's theory, the transition comes in two stages: between the primal sketch and the 2½-D sketch and then between a viewer-centered and an object-centered representation.

### Feature Analyses: Behavioral Tests

A wide variety of behavioral tests have been developed in attempts to demonstrate the existence of separable feature analysis. Psychophysicists have used threshold summation and identification tasks, selective adaptation, and masking paradigms to provide converging evidence for separable channels, early in visual processing, that code orientation, spatial frequency, location, direction of motion, and temporal position (see Graham, 1985, for an excellent review). Treisman (1986) compared some of the same tests with other criteria that might be expected to reflect different stages of perceptual analysis. Thus the early coding reflected in threshold summation, masking, and aftereffects induced by selective adaptation may also mediate the effortless texture segregation explored by Beck (1967), Julesz (1981), and Treisman and Gelade (1980), the features that recombine to form illusory conjunctions when attention is overloaded (Treisman & Schmidt, 1982), and the "pop-out" effect in visual search in which the target is detected equally fast whatever the number of distractors (Egeth, Jonides, & Wall, 1972; Neisser, 1964; Treisman, Sykes, & Gelade, 1977). Tests for separability that may reflect the parts or properties identified in the subsequent analysis of objects include Garner's speeded classification tasks, the city-block metric inferred from similarity judgments, and independence in absolute judgments (Garner, 1974). Garner's tests are all applied to either one or two items, to which attention is at least temporarily directed.

Because the researchers were concerned primarily with exploring and validating behavioral tests for separability, most of

these studies used properties such as color and line or edge orientation, which are likely to be separable at any level, but some researchers have also attempted to test more controversial features. Examples tested by the selective adaptation method include curvature (Riggs, 1973), size changes as a cue to "looming" (Beverley & Regan, 1979), and line arrangement (Foster & Mason, 1980). Examples tested by texture-segregation measures include intersections and line ends, or terminators (Julesz, 1981). Examples using evidence from illusory conjunctions, texture segregation, and search include closure and arrow vertices (Treisman & Paterson, 1984), and examples tested by the parallel search criterion include curved versus straight or angular letters (Neisser, 1964), terminators, connectedness, and acute angles (Treisman & Souther, 1985).

Some researchers have attempted to show convergence between different diagnostics. The most impressive agreement is found within the psychophysical, near-threshold tests that Graham (1985) reviewed. These tests are presumed to reflect the earliest levels of processing. At the other extreme, Garner's criteria, which deal with single attended stimuli or pairs of stimuli, also generally agree with each other in deciding which dimensions are integral and which are separable. Treisman and Paterson (1984) showed correlations across subjects between three criteria in divided-attention tasks—ease of texture segregation, occurrence of illusory conjunctions, and parallel search—using stimuli (arrows) that, for some subjects, appeared to be coded into separable parts and, for others, to possess a unitary emergent feature. Failures to converge on common candidate features using different behavioral diagnostics could simply reflect access to different functional stages. Beck (1966) noted that similarity is determined differently when attention is distributed across the field and when it is focused on one or two items. We infer, for example, that at the early levels of processing, a field of upright *T*s differs more from a field of tilted *T*s than from a field of *L*s because they segregate much better from the tilted *T*s. Yet when subjects are asked to rate the similarity of a single pair, they see the *T* as more similar to the tilted *T* than to the *L*. One explanation for the difference might be that the letters are treated as texture elements in one case and as individuated objects in the other. Attention is divided between texture elements but focused on one object at a time in the similarity judgments, allowing the relation between the component lines to be distinguished (Treisman & Gelade, 1980). Once attention is focused on an object, the relations between its features could become as salient as the features themselves (see the Discussion section of this article).

## Search Tasks and Feature Diagnostics: A Pooled Response Model

The pop-out effect in search may offer one of the most direct tests for separable features, detected through early, spatially parallel and automatic coding. The target is identified preattentively, and its presence tends to "call" attention. There is evidence that preattentive detection can also precede localization; in a substantial proportion of trials, subjects correctly identified a unique feature target despite locating it in the wrong half of the display (Treisman & Gelade, 1980). The performance pattern differs with conjunction targets. In visual search tasks, targets defined only by conjunctions of separable properties (e.g.,
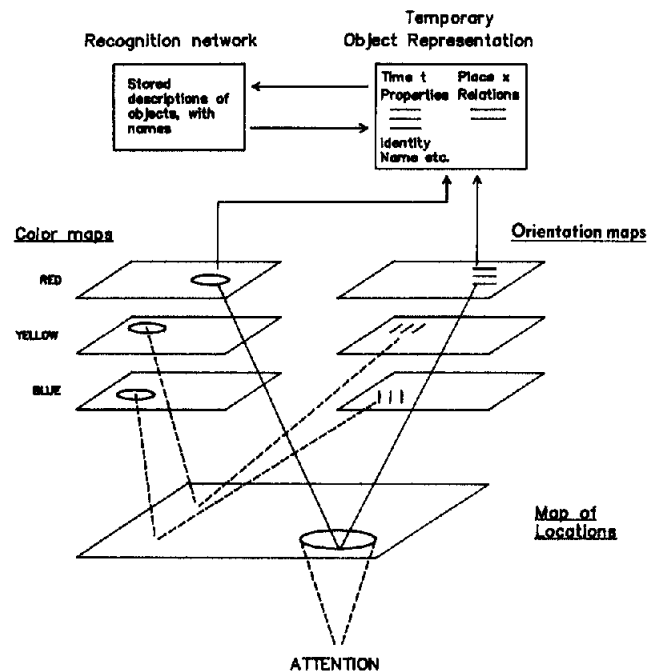


*Figure 1.* Suggested framework to account for perception of features and objects.

a green *T* among green *X*s and brown *T*s) show linear increases in search latency as the number of items is increased. They appear to require serial processing; no pop-out occurs, and correct identification appears to depend on correct localization. We suggest that focused attention, in the sense of a spatially selective "spotlight," must be directed to each item in turn in order to ensure both its localization and the correct conjunction of its properties.

Figure 1 (an expanded version of Figure 9 in Treisman & Souther, 1985) shows the theoretical framework we propose. The medium in which attention operates, according to our hypothesis, is a master map of locations that specifies *where* in the display things are, but not *what* they are. It indicates the number of elements, or filled locations, but not which features occupy which locations. In an earlier article, to account for the occurrence of illusory conjunctions, we described features as preattentively free-floating (Treisman & Schmidt, 1982). The claim is that features are free-floating in the sense that without focused attention their locations are subjectively uncertain or incorrectly transmitted to the level at which the representations of conjoined objects are constructed. However, location information is certainly coded in early vision; many of the feature maps that physiologists have explored are topographically organized. We suggest that feature locations are accessed for further processing and conscious experience only through functional links to the master map of locations, from which they can be serially scanned. Attention selects a filled location within the master map and thereby temporarily restricts the activity from each feature map to the features that are linked to the selected location. The finer the grain of the scan, the more precise the localization and, as a consequence, the more accurately conjoined the features present in different maps will be. A recent

finding by Nakayama and Silverman (1986) suggests that attention can select a plane in the third dimension as well as areas in the frontal plane (see also Downing & Pinker, 1985). The master map may therefore be functionally three dimensional. Attention may select more than one filled location; however, data reported by Posner, Davidson, and Snyder (1980) suggest that attention cannot be spatially split between noncontiguous locations, so simultaneously selected locations will usually be spatially contiguous.

When attention is divided over the whole display, only the presence of a unique feature can be detected, not its location. Even when the target is locally unique and surrounded by contrasting items, preattentive pop-out is precluded if the target's locally distinctive feature is also present elsewhere in the display (Treisman, 1982). For example, a red $X$ surrounded by green $X$s is centrally masked by the presence of red $T$s elsewhere in the display, unless or until attention is focused on its local group and excludes the irrelevant red $T$s. Thus, for a specific target to be detected when attention is evenly divided over the whole display, its defining property must be unique in the display as a whole, not just within its own subregion or group. We have suggested elsewhere that subjects check a pooled response from the relevant feature map for the presence of activity anywhere in that map (Treisman, 1985; Treisman & Souther, 1985). The idea of a pooled response to a particular feature, independent of spatial locations, has also been proposed in computational vision by Ballard (1984) as a tool for segmenting the visual field. In addition to local, spatially indexed properties, he used global feature spaces to signal the presence, but not the location, of particular features.

The pooled response model makes an interesting prediction: A target should be preattentively invisible if and when it is defined only by the absence of a feature that is present in all the distractors. If we measure only a pooled response to the relevant feature, we expect the difference between displays containing $n - 1$ instances of the relevant feature and displays containing $n$ instances to decrease rapidly as $n$ is increased. Once the difference becomes unreliable relative to "noise" in the system, subjects should be forced to search serially. Treisman and Souther (1985) confirmed the predicted asymmetry in search, using as the critical feature an intersecting line either added to or removed from a circle. Search was hardly affected by display size when the target was a circle with an added line among distractor circles without lines, but search increased linearly with display size when the target was the only circle without a line among distractor circles with lines. In a control experiment, in which we expected no asymmetry, we compared search for the presence and search for the absence of green, where "not green" implied red or black among green distractors. In both cases the target popped out despite the difference in the verbal definition of the target, ruling out negation as a linguistic source of the asymmetry. Thus if the absence of a feature implies the presence of another, equally salient feature (as is the case with clearly discriminable colors), no asymmetry is found. We call such features substitutive (cf. Tversky & Gati, 1982).

An asymmetry between the presence and absence of features has previously been noted by Beck (1973, 1982) and by Julesz (1981). Beck found that textural segmentation is stronger for complete triangles among incomplete triangles than for incomplete triangles among complete ones. Similarly, long lines segre-

gate better from a background of short lines than the reverse. Also, subjects made more errors in deciding whether an array of four lines contained a shorter line than in deciding whether it contained a longer line (Beck, 1974). Julesz showed the same with triangles among arrows and reported that spatial grouping facilitates the detection of targets that lack a critical feature (a "texton" in his terms) but has no effect on detection when the targets have the relevant textons and the surrounding distractors lack it. He suggested that the area free of distractor "textons" must be significantly larger than the mean distance between distractors to give convincing evidence for their absence and (by implication?) for the presence of the target. It is not clear in Julesz's account whether physically empty spaces would be confused with targets.

## Search Rates and Group Scanning

The pooled response hypothesis suggests a further possibility that we will call the group-scanning hypothesis. If activity generated by particular features is pooled across the whole display when attention is divided equally over the area, it may be pooled within a smaller subarea when attention is narrowed to exclude the surroundings. When the target and the distractors differ only in degree on one shared dimension, search rates typically vary with the discriminability of the difference. In our earlier article (Treisman & Souther, 1985), we suggested two possible accounts for differing search rates (indicated by different slopes to the linear functions relating search latency to display size): (a) Each item could be checked in turn, taking longer when the target is more difficult to discriminate from the distractors; or (b) subjects might check groups of items in parallel, with group size depending on the discriminability of the pooled feature reponse to groups containing only distractors and to groups in which the target replaced one of the distractors. We preferred the latter hypothesis because the search rates for the most discriminable stimuli were so fast (about 13 ms per item) that they seemed inconsistent with the fastest times we have obtained in conjunction search conditions (Treisman & Gelade, 1980). These search rates average around 60 ms per item for color-shape conjunctions, which may translate into as much as 120 ms if subjects restrict search to items sharing only one of the defining target features (Egeth, Virzi, & Garbart, 1984). There is also direct evidence that subjects do scan groups in parallel when the target would differ from the rest of its group in some unique feature and could therefore be detected without being accurately localized within the group (Treisman, 1982). For example, in search for a green $H$ conjunction target, subjects appeared to scan homogeneous groups of four or nine red $H$s, or four or nine green $O$s, as units rather than serially checking each item within the group.

For discriminations on one shared dimension, subjects should be able to pool the relevant feature activity over groups of items when the difference between target and distractors is large without running the risk of increased misses or false alarms. In fact, Weber's law should determine the discriminability of groups of a given size when they do and do not include a target. This law states that the size of the just noticeable difference is a constant ratio of the background level. According to Weber's law, in deciding whether a target is present within an attended group, subjects will compare the activity in the pooled

Table 1
*Examples of Effects of Group Size on Pooled Response and Weber Fraction*

| Condition | No. of items in group | | | | |
| --- | --- | --- | --- | --- | --- |
| | 1 | 2 | 3 | 6 | 12 |
| High discriminability | | | | | |
| Case A (target 1, distractors 0.1) | | | | | |
| Target present | 1 | 1.1 | 1.2 | 1.6 | 2.1 |
| Target absent | 0.1 | 0.2 | 0.3 | 0.6 | 1.2 |
| Weber fraction | 9.00 | 4.50 | 3.00 | 1.67 | .75 |
| Case B (target 0.1, distractors 1) | | | | | |
| Target present | 0.1 | 1.1 | 2.1 | 5.1 | 11.1 |
| Target absent | 1 | 2 | 3 | 6 | 12 |
| Weber fraction | .90 | .45 | .30 | .15 | .08 |
| Low discriminability | | | | | |
| Case C (target 1, distractors 0.5) | | | | | |
| Target present | 1 | 1.5 | 2 | 3.5 | 6.5 |
| Target absent | 0.5 | 1 | 1.5 | 3 | 6 |
| Weber fraction | 1.00 | .50 | .33 | .17 | .08 |
| Case D (target 0.5, distractors 1) | | | | | |
| Target present | 0.5 | 1.5 | 2.5 | 5.5 | 11.5 |
| Target absent | 1 | 2 | 3 | 6 | 12 |
| Weber fraction | 0.50 | .25 | .17 | .08 | .04 |

*Note.* Hypothetical values are shown for two levels of discriminability and for targets that have more or less of the relevant feature relative to distractors. The Weber fraction is the difference between the activity levels for target present and target absent, divided by the level for target absent.

response of a group containing a target and a group of the same size containing only distractors. Case A in Table 1 illustrates what might happen for different group sizes when the target generates 10 times more activity in the relevant feature detectors than do the distractors, and Case C shows the same when it generates only twice as much. Suppose that the subject sets a criterion for the group size to scan, such that the Weber fraction gives an acceptably low error rate. In Table 1, a Weber fraction of 0.33, for example, would give parallel search for the whole display in Case A, where the target has the relevant feature and the distractors share it only minimally; it would give serial search of triplets of items in Case C, where the distractors are less discriminable from the target.

Now what would happen if the target had less of the shared property than the distractors? It seems that the group-scanning hypothesis predicts a search asymmetry between more and less of a critical feature as well as between its presence and absence. Again, this follows from Weber's law: When the distractors produce a low level of activity, subjects must discriminate a group with more activity (because the target replaces one distractor) from groups with a uniformly low level. On the other hand,

when the distractors produce a high level of activity in the relevant detectors, subjects must discriminate a group with less activity from groups with a level that is uniformly high. Cases B and D in Table 1 illustrate how the Weber fraction would vary in this case, as the group size changes from 1 to 12. The Weber fraction of 0.33 would give serial search of pairs of items in Case B, where the distractors have the relevant feature that the target shares only minimally; finally, serial item-by-item search would be required in Case D, where the distractors have the relevant feature but the target also shares it to a considerable degree. Thus the application of Weber's law to different levels of pooled distractor activity predicts an asymmetry of search for targets with more of the relevant property against a low background level and for targets with less of the relevant feature against a high background level. It may also explain the greater advantage of spatial grouping for the detection of absent features, which Julesz (1981) reported.

So far we have assumed that activity is simply summed in the pooled response. If this were the case, the pooled response would not distinguish extreme or optimal trigger values in a few detectors from less extreme or less optimal values in many detectors. Thus three bright dots might be confused with six dim ones, or one vertical line might be confused with two almost-vertical lines. However, if the pooled response gave the average of the activity in the pooled detectors instead of the sum, this confounding would not arise. Averaging might be achieved if active detectors for the same values inhibited one another. The more that were active, the more inhibitory inputs each would receive. There is physiological evidence for inhibition from identical or similar stimuli located outside the "classical" receptive field of cells in $V_1$, $V_2$, MT, and $V_4$ (Allman, Miezin, & McGuinness, 1985). The pooled response might then be independent of the number of contributing elements and could unambiguously signal the presence of a particular feature. The target's effect on the pooled response to a group of items would still be progressively diluted as the number of active distractors pooled along with it increased. Weber's law would determine the critical group size, exactly as it would if activity were summed. (Note that the hypothesized master map of filled locations would be available to specify the number of elements present and their locations. The pooled response from the feature maps would specify only the presence and average value of any given feature.)

## Review of Search Experiments With Simple Feature Discriminations

In the next section we report a series of findings regarding the determinants of pop-out and search asymmetry in a number of apparently simple discriminations. Our goals in this section of the article are to collect and summarize a large number of findings that we have obtained in search tasks with simple stimuli varying in one relevant property. We use these results to shed light on the functional features extracted in early visual processing, to compare and contrast the different patterns of performance, and to extract generalizations from this overview, relating both to the nature of early visual coding and to the role and mechanism of focused attention. These conclusions will then be discussed within the framework of feature-integration theory.

The experiments using simple stimuli can be divided into five

groups: those testing quantitative dimensions—line length, darkness of grey, and number of lines; those testing spatial properties of a single line—orientation and curvature; those exploring the coding of prototypical values and deviations; those exploring possible emergent features created by the arrangement of two straight lines—intersection, juncture, and convergence; and those testing examples of relational or topological properties—connectedness and containment (inside vs. outside). In our experiments these were all properties of two-dimensional stimuli, whereas in normal perception the input is much richer, with variations in depth, motion, and surface textures. The properties we tested, however, would also characterize the retinal projections of three-dimensional stimuli. To argue for their real-world relevance, one can point to the rapid recognition of outline drawings (about as fast as that of color photographs; Biederman, 1985) and to the fact that many two-dimensional properties (e.g., parallelism, colinearity, symmetry) can be used directly as cues to depth and solid volumes (Lowe, 1984; Witkin & Tenenbaum, 1983).

## General Method

All of the following experiments were conducted using the same procedure and equipment, with only a few exceptions, which are described below and listed in Table 2.

### Stimuli

The stimuli were presented on cards in a Cambridge two-field tachistoscope with a background luminance of about 4.0 mL. Each display was preceded and followed by a white field with a central black fixation dot, and each display remained visible until the subject responded. In most experiments, the display was triggered and the key-press reaction times were recorded by a Corona personal computer, which also gave feedback on errors in the form of an 1100-ms noise burst. In a few cases the response was a vocal "yes" or "no," detected by a Gerbrands voice-operated relay that stopped a sweep timer previously triggered by the onset of the display.

In most cases the stimuli were drawn with black ink pens and stencils. In two experiments the stimuli were adhesive grey or colored dots. The distractor items were scattered haphazardly across a 6.5 × 9.5 cm area, subtending 8.9° × 13.0°. Display sizes were always 1, 6, and 12 items, and either 8 or 12 examples of each type were made with a target present and 8 or 12 were made with no target present. The positions of the targets were constrained so that either 2 (if the total was 8) or 3 (if the total was 12) appeared in each quadrant of the display and at either 2 or 3 different distances from the center.

### Subjects

All subjects were students at the University of British Columbia, who volunteered for the experiment and were paid $4 an hour. Most of the subjects were tested in either one or two of the present series of experiments. Seventy-five of the 103 subjects participated in one of the experiments, 17 in two, 5 in three, 2 in four, and 4 in five. All the subjects had done at least one other reaction time experiment in our laboratory and therefore were familiar with the general setting and requirements. Any subject who made more than 30% errors in any condition of an experiment was replaced.

### Procedure

In each experiment we tested a pair of stimuli, distinguished by what might be a simple, separable feature. Two conditions were always tested

in separate parts of the experiment; these differed only in which of the pair of items was designated the target and which was replicated as the distractor. The order in which these conditions were tested was counterbalanced across subjects. The different display sizes as well as positive and negative trials were randomly mixed within blocks. For experiments in which stimulus orientation was irrelevant or the stimuli were vertically symmetric, the cards were inverted after each block of trials to reduce the possibility that any learning of particular displays would occur and to double the number of target locations tested. The cards were shuffled between blocks for all experiments.

In each condition subjects were told what the target would be and were shown examples of displays with and without it. They were given at least 20 practice trials before each condition, more if they were very slow or inaccurate. Before each trial, they heard either a 300-ms, 1000-Hz tone (in most experiments) or a verbal "ready" signal, both of which were immediately followed by the display, which remained visible until they made their response. Subjects were instructed to respond as quickly as possible while minimizing errors. In experiments with a key-press response, subjects responded by pressing one of two keys. Half of the subjects pressed the right key if a target was present and the left if it was not, and half did the reverse. In experiments with a vocal response, subjects said "yes" if a target was present and "no" if it was absent. Trials on which an error was made were discarded and repeated later in the block. Reaction times more than three standard deviations from the mean for any condition were discarded.

Analyses of variance (ANOVAs) were carried out on the results of all experiments (any effects discussed in this article were significant at least at $p$ .05). In the interest of clarity and brevity the details of the ANOVAs are usually not listed in full.

## Quantitative Dimensions

In our earlier experiment on circles with or without an added line, we interpreted the search asymmetry as reflecting the difference between search for the presence and search for the absence of a feature (Treisman & Souther, 1985). The target with an added line popped out because it produced unique activity in the relevant feature detectors. The target without a line produced none and therefore resulted in only a fractional decrease in the background activity produced by the distractors, all of which had the added lines. If this interpretation is correct, the presence–absence difference may represent only the ends of a continuum of neural response. Between *some* and *none* we could have *more* and *less* activity. To test our claim that pop-out is mediated by a positive signal from the target rather than by faster detection of homogeneity for the simpler distractors, we predict that there should also be a search asymmetry favoring the target that has more of a shared property when target and distractors differ only in degree on a quantitative dimension. We tested the effect of varying the number of distractors in tasks in which it seemed likely that the difference between target and distractors would be coded by a difference in the amount of activity each generated in the same population of functional detectors.

In Experiment 1 we varied the line length of target and distractors; in Experiment 2, their contrast (darkness vs. lightness of grey on a white background); and in Experiment 3, the number of lines (pairs vs. single lines). For each of these dimensions, the empty white field represented a different null value—no length, no contrast, and zero lines. The pooled response model led us to expect the longer line, the darker grey dot, and the pair of lines among singles to be the positively signaled targets against the background of less distractor activity; and the

Table 2
*Summary of Search Experiments*

| Feature tested | No. of cards × trials per card | Response | Subjects | | Target | Search Rates | | Intercept (mean of positive and negative) | % errors (display size) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | Female | Male | | Positive | Negative | | 1 | 6 | 12 |
| Line length | | | | | | | | | | | |
| Easy | 12 × 3 | Key press | 8 | 0 | Short | 14.3 | 28.3 | 504 | 1.7 | 4.4 | 3.2 |
| | | | | | Long | 7.6 | 15.5 | 499 | 0.4 | 3.8 | 3.6 |
| Difficult | 12 × 3 | Key press | 4 | 4 | Short | 40.0 | 81.1 | 565 | 2.3 | 3.2 | 5.3 |
| | | | | | Long | 29.7 | 64.7 | 570 | 2.0 | 3.8 | 5.5 |
| Matched distractors | 12 × 3 | Key press | 7 | 1 | Short | 20.6 | 53.3 | 587 | 0.8 | 2.0 | 4.7 |
| | | | | | Long | 20.4 | 53.0 | 564 | 0.6 | 3.3 | 5.4 |
| Grey | | | | | | | | | | | |
| Easy | 8 × 3 | Key press | 3 | 5 | Light grey | 2.9 | −2.4 | 503 | 2.5 | 2.2 | 1.9 |
| | | | | | Dark grey | 4.8 | −1.7 | 465 | 0.8 | 0.9 | 1.0 |
| Difficult | 12 × 3 | Key press | 3 | 5 | Light grey | 13.7 | 28.6 | 613 | 4.4 | 1.7 | 4.4 |
| | | | | | Dark grey | 5.8 | 19.2 | 597 | 2.1 | 4.9 | 4.7 |
| Number (1 vs. 2) | 8 × 4 | Key press | 8 | 0 | One | 10.5 | 32.5 | 498 | 1.8 | 2.0 | 2.3 |
| | | | | | Two | 1.7 | 7.3 | 480 | 2.0 | 1.3 | 0.9 |
| Curved/straight | | | | | | | | | | | |
| Easy | 8 × 2 | Vocal | 7 | 1 | Straight | 4.2 | 9.8 | 605 | 0.4 | 1.6 | 0.0 |
| | | | | | Curved | 3.1 | 7.0 | 577 | 1.5 | 0.4 | 0.4 |
| Medium | 8 × 2 | Vocal | 7 | 1 | Straight | 12.4 | 22.2 | 598 | 0.4 | 2.3 | 1.6 |
| | | | | | Curved | 3.0 | 11.6 | 577 | 0.0 | 0.8 | 1.6 |
| Difficult | 8 × 2 | Vocal | 7 | 1 | Straight | 29.0 | 54.7 | 598 | 0.0 | 6.6 | 7.4 |
| | | | | | Curved | 6.1 | 12.9 | 598 | 1.5 | 0.3 | 2.4 |
| Control with circle aperture | 8 × 3 | Key press | 5 | 3 | Straight | 83.5 | 124.4 | 533 | 0.5 | 2.5 | 8.2 |
| | | | | | Curved | 18.3 | 31.2 | 588 | 0.5 | 0.3 | 2.4 |
| Line orientation | 8 × 3 | Key press | 4 | 4 | Vertical | 28.3 | 29.6 | 537 | 2.4 | 5.0 | 6.8 |
| | | | | | Tilted | 4.6 | 2.5 | 491 | 1.5 | 1.0 | 2.4 |
| Control with circle aperture | 8 × 3 | Key press | 3 | 5 | Vertical | 17.1 | 17.9 | 564 | 5.0 | 3.7 | 4.2 |
| | | | | | Tilted | 2.0 | 4.3 | 515 | 3.5 | 1.7 | 2.0 |
| Control with tilted frame, head fixed | 8 × 3 | Key press | 6 | 2 | Tilted | 9.6 | 15.7 | 682 | 6.3 | 3.0 | 1.5 |
| | | | | | Vertical | 3.1 | 7.0 | 552 | 2.8 | 0.8 | 1.5 |
| Control with vertical frame, head fixed | 8 × 3 | Key press | 6 | 2 | Vertical | 31.9 | 44.0 | 601 | 2.9 | 7.0 | 5.7 |
| | | | | | Tilted | 5.1 | 7.0 | 495 | 1.5 | 1.3 | 1.0 |
| Control with both target and distractor tilted | 8 × 3 | Key press | 4 | 4 | Less Tilted | −2.3 | 2.4 | 658 | 2.6 | 2.9 | 1.5 |
| | | | | | More Tilted | −6.1 | −2.2 | 609 | 4.4 | 1.3 | 1.6 |
| Color | 24 (8 per color) × 2 | Key press | 2 | 6 | Prototype | 4.7 | 4.9 | 524 | 4.2 | 3.8 | 4.0 |
| | | | | | Deviation | 2.5 | 1.1 | 523 | 4.1 | 3.0 | 3.2 |
| Circles vs. ellipses | | | | | | | | | | | |
| Fixed orientation | 8 × 3 | Key press | 6 | 2 | Circle | 36.4 | 55.6 | 559 | 1.8 | 6.5 | 6.0 |
| | | | | | Ellipse | 10.5 | 18.7 | 510 | 1.5 | 3.6 | 2.8 |
| Varied orientation | 8 × 3 | Key press | 6 | 2 | Circle | 44.1 | 80.3 | 548 | 0.7 | 5.3 | 9.0 |
| | | | | | Ellipse | 10.9 | 19.6 | 482 | 1.9 | 0.8 | 4.1 |
| Intersection | 8 × 3 | Vocal | 8 | 0 | Plus | 16.4 | 23.5 | 494 | 3.2 | 1.0 | 8.5 |
| | | | | | Line | 14.1 | 21.8 | 524 | 1.7 | 1.0 | 5.4 |
| Juncture | 8 × 4 | Key press | 6 | 2 | Angle | 34.4 | 74.4 | 501 | 1.4 | 6.1 | 6.7 |
| | | | | | Lines | 19.4 | 23.9 | 509 | 1.9 | 2.4 | 2.9 |
| Convergence | 8 × 4 | Key press | 3 | 5 | Parallel | 32.2 | 61.3 | 493 | 1.5 | 3.5 | 5.5 |
| | | | | | Converging | 14.6 | 29.5 | 491 | 2.0 | 1.0 | 3.5 |
| Closure and terminators | | | | | | | | | | | |
| Easy | 8 × 4 | Vocal | 5 | 3 | Closed | 6.2 | 13.1 | 535 | 0.8 | 1.2 | 0.8 |
| | | | | | Gap | 1.6 | 8.0 | 504 | 1.0 | 1.4 | 1.0 |
| Medium | 8 × 4 | Vocal | 5 | 3 | Closed | 14.8 | 33.5 | 515 | 1.5 | 1.6 | 1.9 |
| | | | | | Gap | 3.1 | 6.3 | 501 | 0.4 | 1.0 | 0.8 |
| Difficult | 8 × 4 | Vocal | 5 | 3 | Closed | 35.6 | 61.3 | 597 | 1.7 | 2.5 | 6.4 |
| | | | | | Gap | 4.7 | 6.0 | 506 | 1.7 | 1.7 | 1.4 |
| Containment | | | | | | | | | | | |
| Convex | 8 × 4 | Key press | 3 | 5 | Inside | 24.0 | 41.3 | 457 | 0.9 | 2.2 | 6.7 |
| | | | | | Outside | 8.9 | 15.3 | 492 | 4.1 | 2.8 | 6.2 |
| Concave | 8 × 4 | Key press | 3 | 5 | Inside | 30.0 | 65.9 | 496 | 3.1 | 4.5 | 9.0 |
| | | | | | Outside | 12.9 | 53.1 | 522 | 3.0 | 6.4 | 4.1 |
| Control convex | | | | | | | | | | | |
| No dot | 8 × 4 | Key press | 6 | 2 | Outside | 15.6 | 39.7 | 480 | 1.7 | 2.3 | 2.7 |
| Dot | 8 × 4 | Key press | 6 | 2 | Outside | 7.1 | 17.3 | 518 | 2.7 | 0.8 | 2.9 |

shorter line, the lighter grey dot, and the single line to be signaled only by a reduction of activity from a higher background level produced by the more extreme distractors.

Experiments 1 and 2 included two levels of discriminability to test whether search would become parallel when discriminability was high, and if so, whether an asymmetry would remain, suggesting a contrast between presence versus absence instead of more versus less. If both versions of the task became parallel, this would suggest the presence of two substitutive features. If only one version gave parallel search, we would infer that one end of the relevant dimension was positively coded, with the other represented, only by default, as the absence of the first.

## Experiment 1: Line Length

In both the easy and the difficult condition, the longer line was 8 mm (subtending 1.1° at a distance of 42 cm). In the difficult condition the shorter line was 6.5 mm and in the easy condition it was 5 mm. All the lines were vertically oriented and scattered haphazardly in the display. Examples are shown in Figure 2a. Different subjects were tested in the two conditions.

The results, shown in Figure 2b and in Table 2, confirmed the hypothesis that a search asymmetry would be present and that it would favor the more extreme value as target, the one we assumed would elicit more activity in the population of detectors. Search was affected by display size for both targets, but more strongly for the target with less of the relevant feature. The results support our suggestion that the asymmetry between pop-out for presence and serial search for absence reflects the two ends of a continuum of discriminability that includes *more* and *less* as well as *some* and *none*. Pop-out depends on the presence of activity on a silent background, and slopes are less steep when the target produces increased activity against a low background than when it results in decreased activity relative to a high background.

## Experiment 1a. Line Length: Search With Matched Distractors

The account we have given, in terms of Weber's law and a pooled response, attributes the search asymmetry to the different distractor backgrounds rather than to the direction in which the target contrasts with the distractors. The smaller target is harder to find, not because it is smaller, but because the distractors are larger in this condition than in the other. They therefore set a higher level of background activity against which the difference introduced by replacing a distractor with a target must be judged. It seemed important to test this claim. Experiment 1a again used lines of different lengths, testing both a larger and a smaller target among the same medium-length distractors and equating the ratios of the lengths in the two conditions. We predicted no asymmetry of search latencies in this experiment because the Weber fraction was the same in the two conditions.

The displays were the same as in Experiment 1 except that the distractors in both sets were 7.5 mm long, subtending 1°; the target in one condition was 10 mm long and, in the other condition, 5 mm long. Figure 2c and Table 2 show the search latencies we obtained. Clearly, the asymmetry we found in Experiment 1 was no longer present. When the distractor background was the same and we equated the ratio of the difference

between target and distractor lines to the distractor line length, it made no difference whether the target was larger or smaller than the distractors.

In our previous article (Treisman & Souther, 1985), the search asymmetries we described were always shown when a given pair of stimuli exchanged roles in the search task, not when two targets differed in opposite directions from a single set of distractors. If we are correct in assuming, for example, that detecting a closed circle among circles with gaps involves discriminating differences in a shared feature (the continuous dimension of degree of closure), the model should predict that it is no easier and no harder to detect a closed circle among circles with gaps than to detect a circle with a larger gap among the same distractor circles with gaps.

We will now look at two other dimensions on which stimuli are likely to differ quantitatively in the amount of activity they generate to see if they also give rise to a search asymmetry, and, if so, whether it favors the more extreme target among the less extreme distractors.

## Experiment 2: Contrast

We used two sets of displays to test two different levels of discriminability. In the easy condition, the displays consisted of dots subtending 1.1° in two different greys on a white background. The darker grey approximated Munsell value 5.5, and the lighter grey Munsell value 8. In the difficult condition, the dots subtended 0.8°, and the corresponding Munsell values were 6 and 7. Different subjects were tested in these two conditions.

## Experiment 3: Number (or Proximity) of Lines

In one condition the distractors were single 7.5-mm lines set at least 14.3 mm apart (subtending 1.0° and separated by at least 1.95°) and in haphazardly selected orientations. The target was a pair of lines, each 7.5 mm long and at random orientations, placed so that they were completely contained within an imaginary circle with an 11.1-mm diameter (subtending 1.5°). In the other condition, the distractors were pairs of lines (with the same spatial constraints), and the target was a single line, again set at least 14.3 mm (1.95°) from the nearest distractor. Examples are shown in Figure 3a. Eight new subjects were tested in these two conditions.

The results of Experiments 2 and 3 are shown in Figures 3b and 4 and in Table 2. Again, all showed a search asymmetry favoring the more extreme value as target. This time, however, with the easier discriminations the search functions were almost flat. This appeared to be the case both for dark and light grey dots in the easier condition and for target pairs when the number of lines was the relevant factor.

Search on quantitative dimensions could be parallel for either of two reasons: (a) if different and separable populations of feature detectors responded to the target and to the distractors or (b) if the group size for which the pooled responses were discriminable exceeded that of the largest display tested (12 items in these experiments). In the first case, we would expect no search asymmetry. The dark and the light grey dots in the easier experiment may, according to this hypothesis, have activated separate sets of detectors, giving flat search functions for both darker and lighter targets. In the second case, there could be a
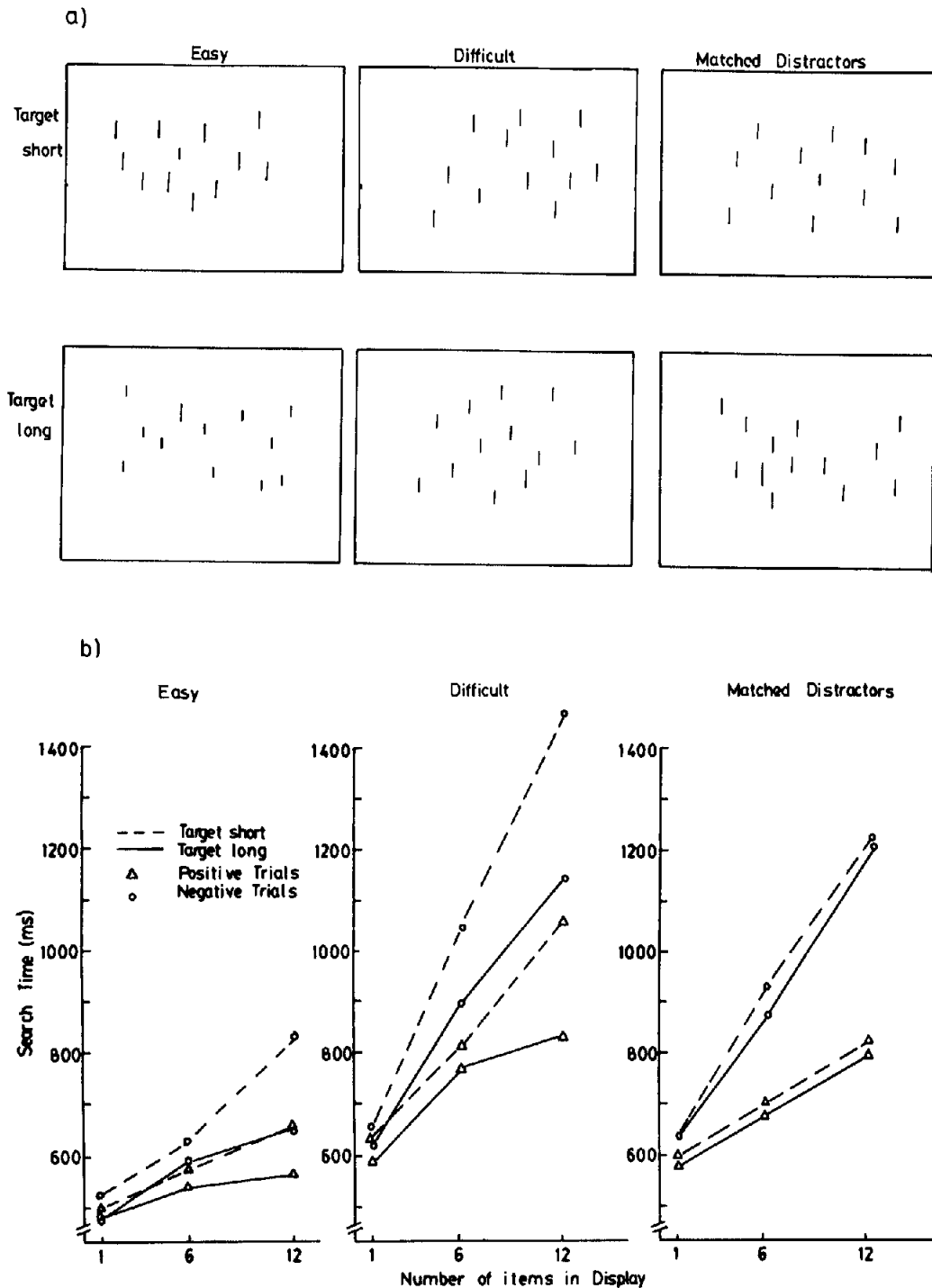
a)



b)



*Figure 2.* (a) Examples of displays testing search for targets defined by differences in line length and (b) search latencies in Experiments 1 and 1a—line length.

level of discriminability at which the higher value target would pop out and the lower value would not (see, for example, Table 1). This seems to have been the case for the paired lines versus the single lines. The experiment does not pinpoint the exact nature of the relevant property: It could be the number of lines or of terminators, their proximity, or even a doubling of contrast present at a low spatial frequency. Along any of these di-

mensions, the pairs of lines would produce more activity, and the single lines less. On the other hand, when the single line was the target among pairs of lines as distractors, the reduction in activity for target present compared with target absent appeared to be detectable only by serial scanning of smaller groups.

The asymmetry between single-line and paired-line targets casts some doubt on the idea that local counting or "subitizing"
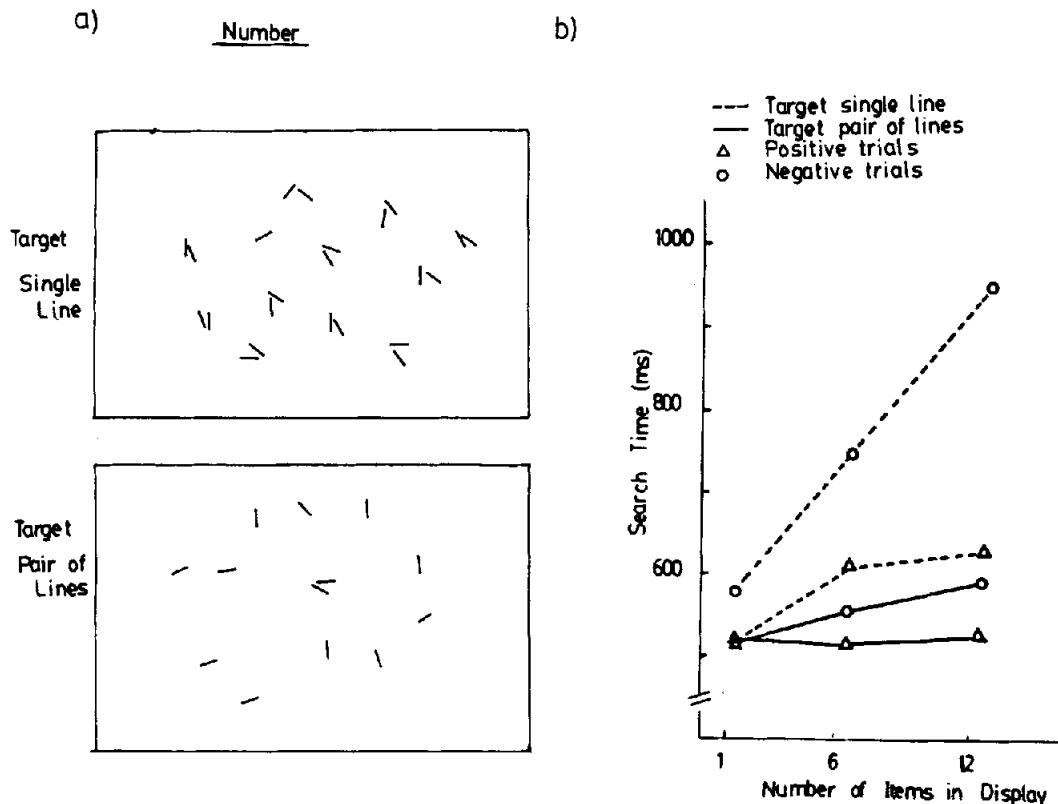
*Figure 3.* (a) Examples of displays testing search for targets defined by number
(two vs. one) and (b) search latencies in Experiment 2—number.

occurs automatically in early vision. Julesz (1984) proposed that "the preattentive system utilizes the textons in the simplest possible way, by counting their numbers (densities)" (p. 597). "This rapid counting is called 'subitizing,' and with up to four or five items can be accomplished without error" (p. 609). Sagi and Julesz (1985) reported that subjects are equally accurate in counting one, two, three, and four targets in brief exposures, as if the number of distinct textons in a display were directly available without serial scanning. However, if counting or subitizing were automatic, one might expect the single line (one item) in our experiment to be at least as easily detected as the pair (two items).

### Line Curvature and Line Orientation

In the next experiments we tested two of the simplest attributes of a single line—the contrast between straight and curved and between vertical and tilted. Both contrasts are essential to defining more complex shapes. Both are likely to be preattentively coded because they are plausible candidates for explaining the demonstrated pop-out of *S*s among *T*s and *X*s (Treisman & Gelade, 1980) and of tilted *T*s among vertical *T*s (Beck & Ambler, 1972). Our aim was to see whether any asymmetry would be present between performance with a curved (or tilted) target among straight (or vertical) distractors and with a straight (or vertical) target among curved (or tilted) distractors. Using the analogy with *more* and *less* on the previously tested quantitative dimensions, we suggest that the search asymmetry can be

used as a diagnostic to determine whether one end of a qualitative dimension produces more activity than the other, or whether each is coded separately. With both curvature and orientation, one value (straight or vertical) can be taken as standard and unique for that dimension. Other stimuli can take a range of values that depart to various degrees from the standard value. We were interested in the possibility that a unique coding exists for the standard value, with deviations represented as reduced activity relative to the standard value. Alternatively, it may be the case that deviations from the standard are positively coded, leaving the standard to be detected only by default. A straight line has straightness and lacks curvature; a curved line has curvature and lacks straightness. Both properties might be coded, or only one, leaving the other to be inferred from the absence of response in the relevant detectors.

### Experiment 4: Curvature

We tested three levels of discriminability on the same subjects, in separate blocks, with order counterbalanced both within and between subjects. The curves were arcs of circles with 28.6 mm, 14.3 mm, and 9.5 mm diameters, (subtending 3.90°, 1.96°, and 1.30°, each with 9.5 mm (1.30°) separation between their endpoints. To exclude the possibility that either line length or the spatial separation of the line ends could be used as alternative cues for the discrimination, the straight lines varied in length, with half matching the length of the arc and half matching the separation of the endpoints in each condition.
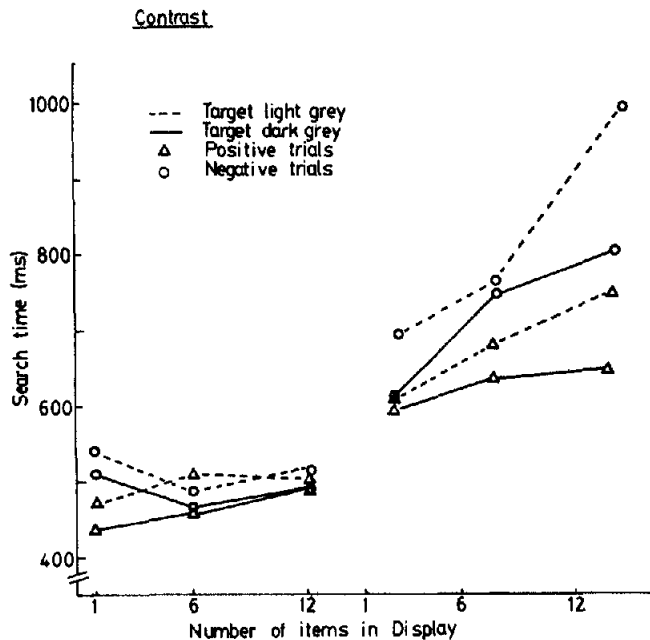
Contrast



*Figure 4.* Search latencies in Experiment 3—contrast. (More discriminable greys on left and less discriminable greys on right.)

Figure 5a shows the displays used to test straight and curved targets.

Figure 5b shows the mean search times in each condition. The most striking aspect of the results is the asymmetry between the search times, depending on whether the target was the line or the curve. When subjects were looking for a single straight line in a background of curves, they appear to have checked items or groups of items serially. The slope of response latencies against display size increased sharply as the discrimination became more difficult. The intercepts showed no systematic effect of discriminability. The functions were all close to linear, and the ratios of positive to negative slopes all approximated 0.5 (averaging 0.43, 0.56, and 0.53), which suggests a serial self-terminating search. The curved targets, on the other hand, were found, on average, much more rapidly and with much less effect of the number of distractors. With increased display size and with decreased curve discriminability, the search times did increase significantly, but the effects were much smaller than with the line targets. There is no support here for the suggestion that curves are coded visually as conjunctions of straight segments of changing orientation. This would force serial search for curves among lines of varied orientations. Instead, curvature appears to be sensed directly.

## Experiment 5: Orientation

The second feature of simple lines that we tested was orientation. The displays contained 7-mm lines subtending 0.95° that were either vertical or tilted 18° to the left. They were scattered haphazardly in an area subtending 7.8° × 6.8°. Examples are shown in Figure 6a.

The results are shown in Figure 6b and in Table 2. Here again we found a striking asymmetry, and again it favored the non-

standard value. A tilted target was detected equally fast for all display sizes tested, whereas a vertical target among tilted lines was found more slowly the more distractors were present.

Comparing the results of both experiments to the analogous performance in the earlier experiment on intact circles and circles with intersecting lines (Treisman & Souther, 1985), we would be led to conclude that the deviating values—the curved and the tilted lines—are coded as feature presence, whereas the standard values—the straight and the vertical lines—are coded as the absence of the critical feature, distinguishing the two stimuli. The results suggest, then, that the visual system codes curvature and tilt as visual primitives. The results do not distinguish two possible ways of coding straight and vertical: They could be represented simply by the absence of activity in the detectors for curved and for tilted (i.e., as the null or default values on those two dimensions). Another possibility, however, is that straight and vertical are coded as the presence of activity in a population of detectors for these standard or reference values and that the same detectors are also activated (almost as much) by the curved or tilted lines. Following the analogy to the standard circles and circles plus lines in the Treisman and Souther (1985) experiment, we suggest that the curved or tilted lines are coded as straight or vertical lines with an additional feature marking the nature of the deviation, just as the circle with the added line is coded as the standard circle with an additional feature (the intersecting line). This interpretation may be preferable in light of results from other experimental paradigms showing more accurate coding and easier labeling of standard values when the stimuli are presented one at a time (e.g., Attneave & Olson, 1967; Rosch-Heider, 1972). If it is correct, the straight and vertical lines would have no unique feature to distinguish them from the curved or tilted distractors. Attention would therefore be directed serially to each item in turn in order to locate the one line that lacked the additional distinctive property, whether curvature or tilt.

Although it may initially seem implausible that curvature and tilt should be positively coded as additional features, whereas straightness and vertical orientation are not, it may be adaptive to signal deviations from standards as added features that generate increased activity. This should maximize the transmission of the informative aspects of the visual input. Thus early vision may generate distinctions analogous to those drawn by linguists, both in phonology and in semantics, between the marked and the unmarked ends of a dimension. We discuss these results further in the context of Experiment 6.

*Frame effects.* Two alternative accounts of the search asymmetry for curvature and tilt should be considered first. One is that the asymmetries of search performance are generated by visual frame effects. In both cases, the cards were shown in a rectangular aperture in the tachistoscope. The frame therefore had edges that were both straight and vertical. Perhaps these frame edges generated enough activity in the functional detectors for straight or vertical to drown the extra activity generated by the straight or vertical targets. Only the curved or tilted targets would then have had a truly unique value in the displays we used. To test this possibility we replicated the two experiments using circular apertures instead of rectangular ones.

*Experiment 4a.* For the straight and curved line displays, the curvature of the aperture (a hole in a black card with a 2.29° diameter) matched the curvature of a new set of curved lines,
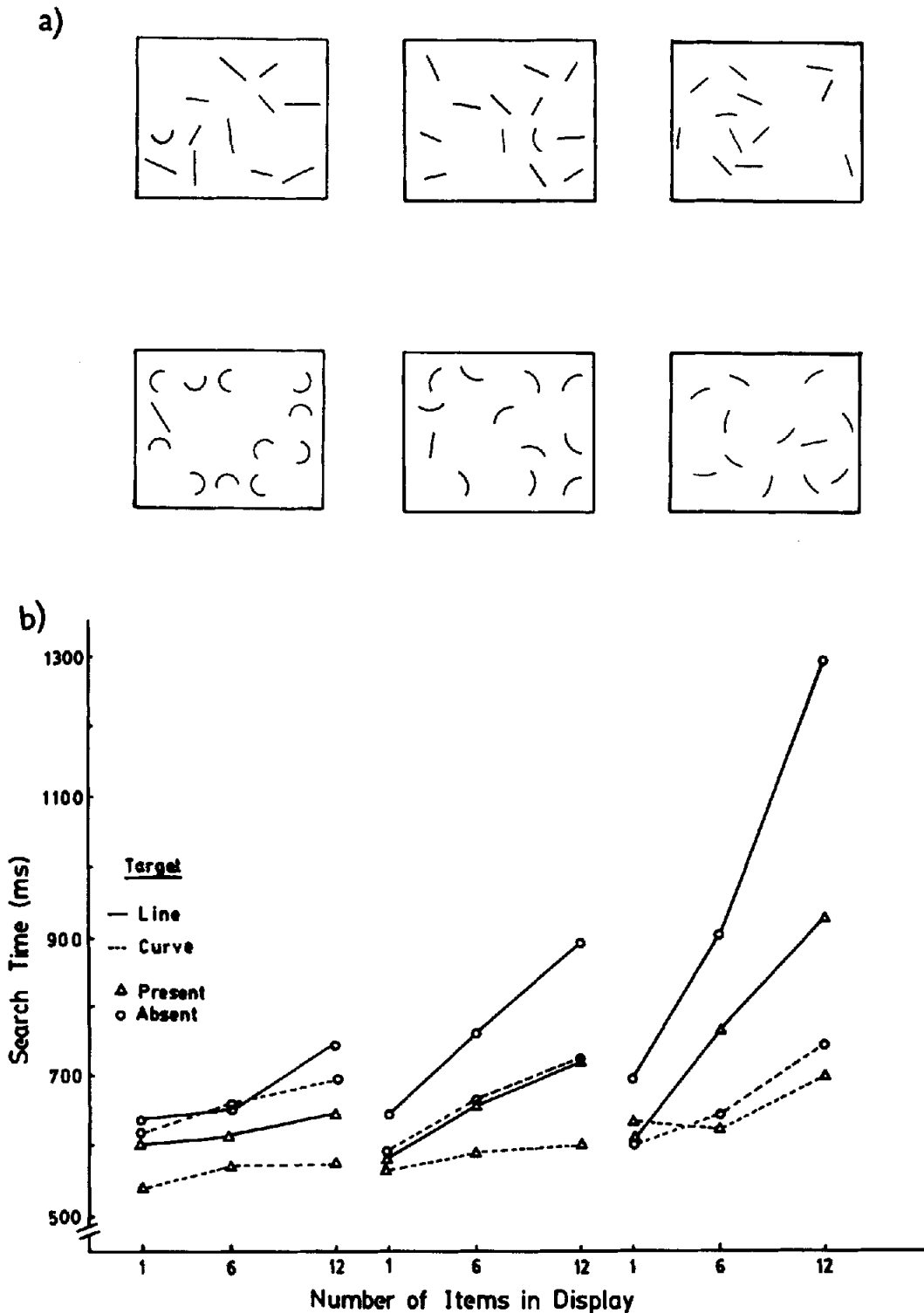
*Figure 5.* (a) Examples of displays testing search for targets defined by curvature or straightness and (b) search latencies in Experiment 4—curvature.

which were shorter (0.64°) and therefore less discriminable from straight than any of the lines tested in Experiment 4. They were also more densely packed, so as to fit into the much smaller area. The same search asymmetry was present, favoring the curved over the straight target. The slopes averaged 18.3 ms per item for positive and 31.2 ms for negative displays with the curved target, and 83.5 ms per item for positive and 124.4 ms for negative displays with the straight target.

(a)

(b)
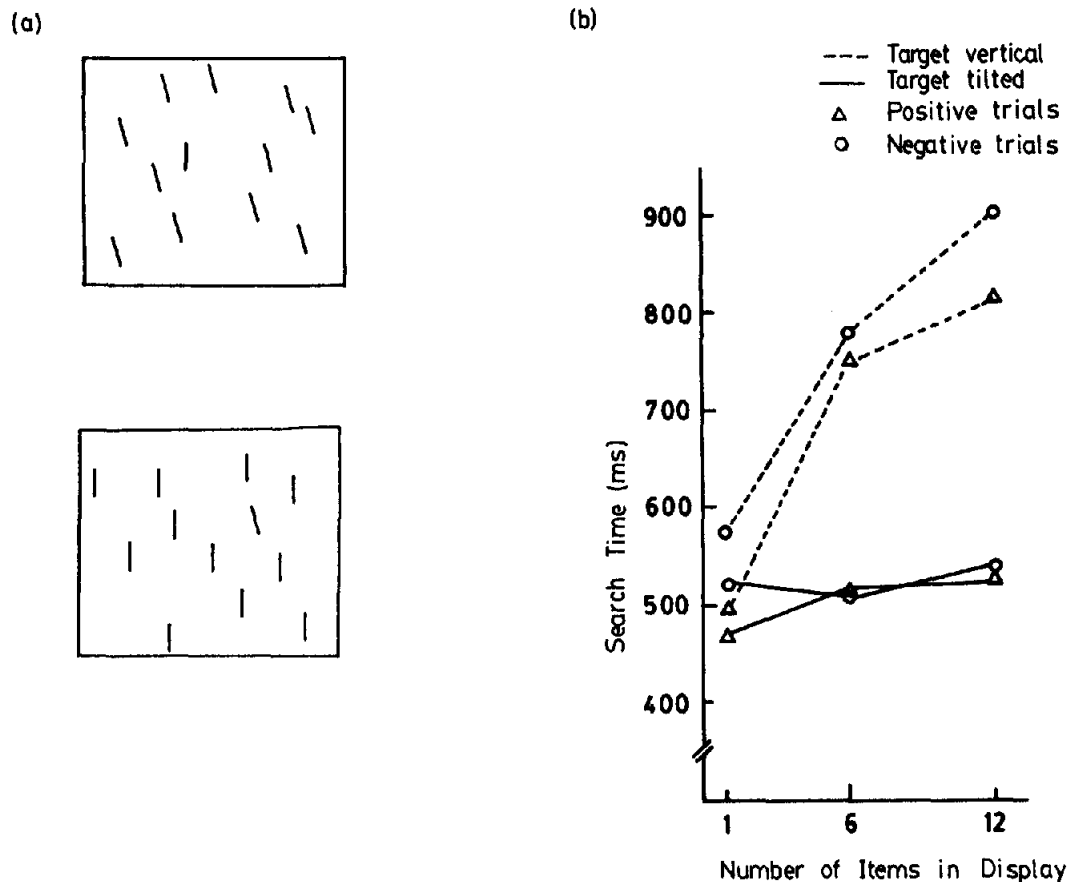


*Figure 6.* (a) Examples of displays testing search for targets defined by line orientation and (b) search latencies in Experiment 5—orientation.

*Experiment 5a.* For the vertical and tilted line displays, the curved aperture was larger, with a 7.5 cm diameter, subtending 10.2° at the viewing distance of 42 cm. Our aim was to have all orientations equally present in the frame rather than to match a particular degree of curvature of the stimuli. Here the asymmetry was also still present but somewhat reduced, although not significantly on this between-subjects comparison. The mean slopes averaged 17.1 and 17.9 ms per item for vertical targets on positive and negative trials, respectively, and 2.0 and 4.3 ms per item for tilted targets.

*Experiment 5b.* Because the change of frame seemed to have some effect on vertical targets, we conducted another experiment, this time with a tilted rectangular frame that was drawn in black ink around the display lines on the cards and placed at the same orientation as that of the tilted lines. We compared this tilted frame condition with a vertical frame condition in which a frame with vertical and horizontal sides was drawn around the distractors. The frames measured 5.7 × 5.0 cm and subtended 7.7° × 6.8°. Subjects' heads were fixed upright by using a chinrest and frame. An asymmetry of search was present in both cases, but it was reversed with the tilted frame. The slower search in each case was for the target line that was aligned with the frame, whether tilted or vertical. Search rates were 31.9 and 44.0 ms per item for positive and negative trials, respectively, when the targets were vertical and aligned with a vertical frame, compared with 5.1 and

7.0 for tilted targets, misaligned with a vertical frame. Search rates were 9.6 and 15.7 ms per item for tilted targets aligned with the tilted frame and 3.1 and 7.0 ms per item for vertical targets misaligned with the tilted frame.

From these results we can conclude the following: (a) the effect of display size in search for straight and for vertical targets was not due solely to competing activity produced by the frame (because it was still present, at least to some degree, with circular frames); and (b) the null, or standard, value for line orientation is at least partly defined by alignment with the edge of a visible or inferred framework rather than simply the one that is vertical on the retina or with respect to gravity.

Although consistent with the other feature-search results in showing the predicted search asymmetry, the results with line orientation depart from the typical pattern in another respect: The functions relating latency to display size for the aligned targets were in each case negatively accelerated rather than linear, and the ratios of positive to negative slopes were closer to 1.0 than to 0.5. The explanation may be linked to our account of the frame effect. It is possible that when the number of distractors increases from 6 to 12, they begin to provide an alternative frame against which even the "frame-aligned" target is perceived as misaligned. Alternatively, with increasing density, a new emergent, or relational, feature, such as convergence or divergence of adjacent lines, may facilitate search, at least when

the target is present. Sagi and Julesz (1987) have suggested that search for targets defined by orientation becomes parallel only when the distractor density reaches a critical point (with two item lengths separating adjacent stimuli). Our results conflict with this conclusion because they show parallel search even for less dense displays of 1 to 6 items, provided that the target is tilted or misaligned with the frame. However, Sagi and Julesz's hypothesis is consistent with the change we found in search rates between 1 to 6 and 6 to 12 when the target was vertical or aligned with the frame. Search for these more difficult targets may switch to dependence on a relational feature of adjacent lines when these are in sufficiently close proximity.

*Target or Distractors With Standard Value?*

A second alternative explanation for search asymmetries is that they reflect, not so much a more difficult task when the target has the standard value (straight or vertical), but an easier task when the distractors have the standard value. We have assumed so far that the preattentively coded feature that mediates parallel detection is the one that characterizes the target. The results with quantitative dimensions strengthened our confidence in this belief because search was faster when the target had more of the relevant property. In the present experiments, however, where pop-out seems to occur for targets that deviate from a standard value but not for targets that embody it, an alternative account would be that search is easy and parallel when the distractors are standard and therefore easy to code. Simple, special values like "straight" or "vertical" might be codable in parallel when replicated across the display, whereas more complex values like "curved" or "tilted" are not.

We can rule out this second alternative account, at least for the tilted lines, because we also ran the original subjects (of Experiment 5) in a condition in which both target and distractors were tilted (both in the vertical aperture). The target and the distractors differed again by 18°, with the target either more or less tilted than the distractors (18° or 36° from the vertical). In both cases, the search latencies were unaffected by the number of distractors; the slopes averaged −6 and −2 ms per item for the 36° target, and −2 and 2 ms per item for the 18° target for positive and negative trials, respectively. Performance was slower with both target and distractors tilted than with only the target tilted: The intercepts averaged 609 ms for the 36° target and 657 ms for the 18° target, compared with 491 ms for the 18° target among vertical distractors. However, the only condition in which search latencies were affected by the number of distractors, suggesting serial search with focused attention, was the condition with a vertical (or frame-aligned) target among tilted distractors. It seems, then, that there is a special difficulty in detecting a standard target rather than a special ease in coding standard distractors.

Our original conclusion, that standard values of orientation and straightness are represented only as the absence of a distinctive feature (because they share the reference value with the tilted or curved lines), seems to fit the data from this enlarged set of experiments better than the alternative hypotheses that we attempted to rule out. Neither a straight nor a vertical (or frame-aligned) target appears to evoke activity in a unique feature map that could trigger fast and spatially parallel detection in search, whereas a curved and a tilted (misaligned) target do

trigger such detection, at least when they are sufficiently discriminable from the distractors. Separability appears to be an asymmetric relation for values within a single dimension as well as for different dimensions (Garner, 1974).

## Prototypes and Deviations of Shape and Color

To test the idea that search asymmetries reflect visual coding of at least some qualitative properties as deviations from a standard, or reference, value, we conducted two more experiments, explicitly testing search for a prototypical stimulus among deviations and the reverse. The two properties we chose to test were a prototypical shape (a circle) with shapes that deviated from it (ellipses) and prototypical colors (red, blue, and green) with deviating colors (magenta, turquoise, and lime).

### Experiment 6: Circles and Ellipses

The first test for prototype effects in visual search used circles and ellipses. These shapes raise two questions of interest within the present context. First, is there an asymmetry favoring target shapes that are less standard or prototypical than the distractors, as there appears to be with the dimensions of tilt and curvature? A circle is probably the simplest possible shape as well as one of the most familiar. An ellipse is more complex and can naturally be described as a transformed circle, whereas describing a circle as a transformed ellipse sounds strange (Tversky, 1977). One might expect the visual code for circles to be simpler or more economical, which might make them easier to detect in a search task. However, our results with curved versus straight lines and tilted versus vertical lines suggest that the reverse might be true. If a general property of perceptual coding is that it gives least response to standard values and represents stimuli as departures from a standard or norm, the asymmetry might be in the opposite direction. The circle would then represent the default, or null, value on the dimension distinguishing tall, thin ellipses from short, fat ones. In this case, circle targets would be found only through a serial search to locate the one stimulus that lacked any degree of elongation. There are alternative accounts for any circle–ellipse asymmetry that seem less plausible but would need to be excluded by further experiments: For example, subjects might use the maximum curvature of the outline or the minimum distance between sides. If these fixed cues were used rather than the relational one, one might expect the task to be more difficult when the orientation of the ellipses was varied randomly, making the locations of the maximum and minimum curvature and the minimum separation less predictable.

The second question is more general and concerns the preattentive coding of shapes varying only in a relational property. Most shapes appear to be coded as conjunctions of more elementary parts, such as lines and curves, with perhaps some additional emergent features such as closure (Treisman & Paterson, 1984). Some simple shapes, however, may be better described as differing primarily through a simple transformation, such as stretching or shear, but otherwise sharing the same components. An example is the contrast between circles and ellipses. Are relational properties of shape, like the ratio of height to width, coded preattentively as simple features, or are they identified only as conjunctions of a particular height with a par-

ticular width? In the next experiment, the apparent area of the circles and ellipses was matched as closely as possible. If either target were to pop out, it would suggest that stimuli differing in a global attribute of shape can be distinguished preattentively, in the same way as stimuli differing in a particular local component or property.

The display contained circles with 7-mm diameters (subtending 0.95°) and ellipses 8.5 mm long (subtending 1.16°) with a maximum width of 6 mm (subtending 0.82°). In one condition the orientation was fixed (the ellipses were always vertical); in the other condition, the ellipses were haphazardly oriented. Figure 7a shows examples. The same subjects were tested in both conditions, in counterbalanced order.

The mean search latencies are shown in Figure 7b and in Table 2. The main findings can be summarized as follows: Neither target popped out, but there was a large asymmetry favoring search for the target ellipse rather than the target circle. Search for the ellipse was fast, suggesting that groups of circles could be checked in parallel for the presence of a target ellipse, whereas this was impossible for a target circle among distractor ellipses. There was no effect of fixed versus varied orientation on search for ellipse targets, but varied distractor orientations did slow search for the target circle.

What conclusions can be drawn about the preattentive coding of shapes? It seems that neither elongation (height to width ratio of 1.42 instead of 1.0) nor the property of global symmetry is a primitive feature at the preattentive level. It is very likely, however, that if the ellipses had been sufficiently elongated, they would have emerged preattentively. At the extreme, it is likely that they would recruit a different set of functional detectors—those responding to oriented bars as opposed to spots. Our stimuli, although easily discriminable when receiving attention, appear to fall in the range where different height-to-width ratios are not discretely coded in separate functional maps.

More interesting is the finding of yet another pronounced search asymmetry. Again it is in the predicted direction, with deviating stimuli proving easier to find than prototypical or standard stimuli. The fact that orientation had no effect on search times for the ellipse rules out the possibility that subjects were simply using either vertical height or horizontal width alone as target features. The elongation of one axis relative to the other is a more likely basis for discrimination, given the absence of any difference in performance between a condition in which the horizontal and the vertical widths were fixed and one in which they could take on any of a range of values. The circles, on the other hand, were harder to find among ellipses of varied than fixed orientations, as if it were harder (or impossible) to group the ellipses and check a pooled response to elongation when its spatial direction was unknown.

## Experiment 7: Color

The second test of prototype effects on visual search used "good" central colors and deviating colors. Color perception is one of the domains in which standard, or prototypical, values were first thought to play a role. Berlin and Kay (1969) analyzed color terms across many different natural languages and found a clear hierarchy determining which colors were given names. Languages vary considerably in the number of color terms they lexicalize, but they select the colors that they do label in the
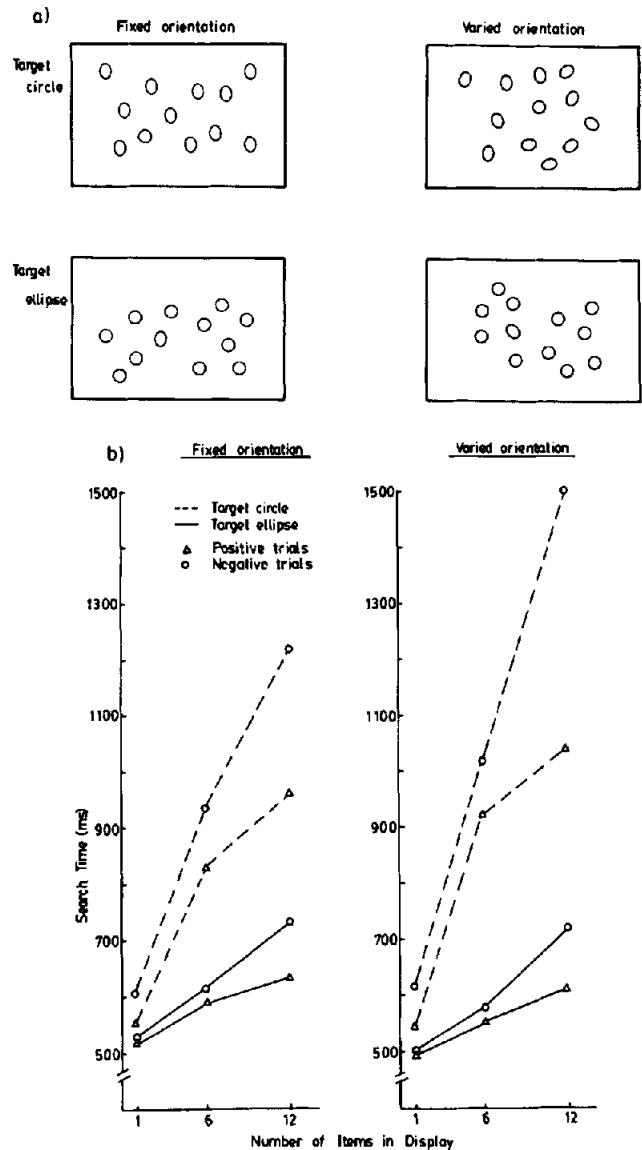


Figure 7. (a) Examples of displays testing search for circles and ellipses and (b) search latencies in Experiment 7—circles and ellipses.

same rank order and differ only in how far down the ranks they go in attributing names to regions of color space. There is also considerable agreement across different language groups about which particular hues are seen as the best examples, or prototypes, for the color terms. Rosch-Heider (1972, 1973) showed that even the Dani of New Guinea—a culture in which no chromatic color terms are used—found it easier to recognize the prototypical colors and to learn categories organized with these as their focal points. In Experiment 7 we explored the possibility that a search asymmetry would favor detection of a deviating color among distractors that are prototypes, relative to detection of prototypical color targets among distractor colors that deviate from them. This would test the generality of our previous conclusion and might also link it more closely to physiology. There is neural evidence for separate color channels coding red versus green and blue versus yellow (De Valois & Jacobs, 1968).

The displays consisted of color dots, 6 mm in diameter, subtending 0.82°. Three pairs of colors were used: red and magenta, green and lime, and blue and turquoise. The dots were punched out of Letrafilm Pantone color/tint overlay (for the blues and greens) and out of Pantone Letrafilm matt (for the red and magenta), and they were stuck to the display cards in haphazardly selected locations. The dots approximated the following Munsell colors (some by interpolation): red = 5R, 5, 14; magenta = 5RP, 5, 14; green = 2.5G, 6.5, 11; lime = 7.5G, 6.5, 11; blue = 2.5PB, 5.5, 10; turquoise = 10BG, 6, 10. Thus the red differed from the magenta by about four Munsell steps, the blue differed from the turquoise by about five Munsell steps, and the green and lime differed by only about two steps on the hue scale. Within each pair, the dots were approximately matched in saturation and chroma. The red, green, and blue were among the hues chosen by Rosch-Heider (1973) as central colors, and the other three hues were either peripheral or internominal.

The results are shown in Figure 8 and in Table 2. Response latencies were significantly longer when the prototypical values defined the targets, $F(2, 14) = 18.42$, $p = .0036$, and there was a significant interaction with display size, $F(2, 14) = 20.26$, $p = .0001$. There were also significant differences between the three color pairs (red/magenta, green/lime, and blue/turquoise, with the least discriminable green/lime pair giving the longest response times), but there were no interactions between color pair and any other variable (except the highest order four-way interaction with prototypical target vs. deviation, display size, and positive vs. negative trials, which is difficult to interpret). The effects were in the predicted direction, given the earlier findings and our interpretation of them. That is to say, the prototypical colors were found more slowly and with more effect of distractors than the deviating colors. However, the effects were much smaller than with other dimensions. It seems unlikely that the effects were so small simply because the discriminations were very easy. The intercepts were no lower than average, and the error rates were higher than for any other experiment giving equally fast and flat search functions. There is a hint in these results that parallel processing is more natural for color than for properties of lines or shapes, even when the discriminations are difficult and accuracy is not guaranteed.

Another point of interest is the longer latency for single items than for six items on negative displays with a deviating color as target, $t(7) = 2.68$, $p < .05$. Subjects were slower, for example, to decide "no, this is not magenta" when only one red item was presented than to decide "no" when six matching red items were presented and no contrasting item was present. A similar disadvantage to single displays was found in the contrast task (Experiment 2) with the easier grey targets, where negative displays of one item received slower responses than negative displays of six items for both dark and light targets, $t(7) = 7.44$, $p < .001$, and $t(7) = 2.76$, $p < .05$, respectively. The pattern suggests that with negative trials on color or contrast, subjects may find it easier to code the homogeneity of target and neighboring distractors than to code the absolute value of each separate distractor. Again, this implies spatially parallel processing at least for adjacent items.

## Implications for Pooled-Response Model

It may be worth trying to link the prototype–deviation asymmetry to neural channels for color and to use the analogy to
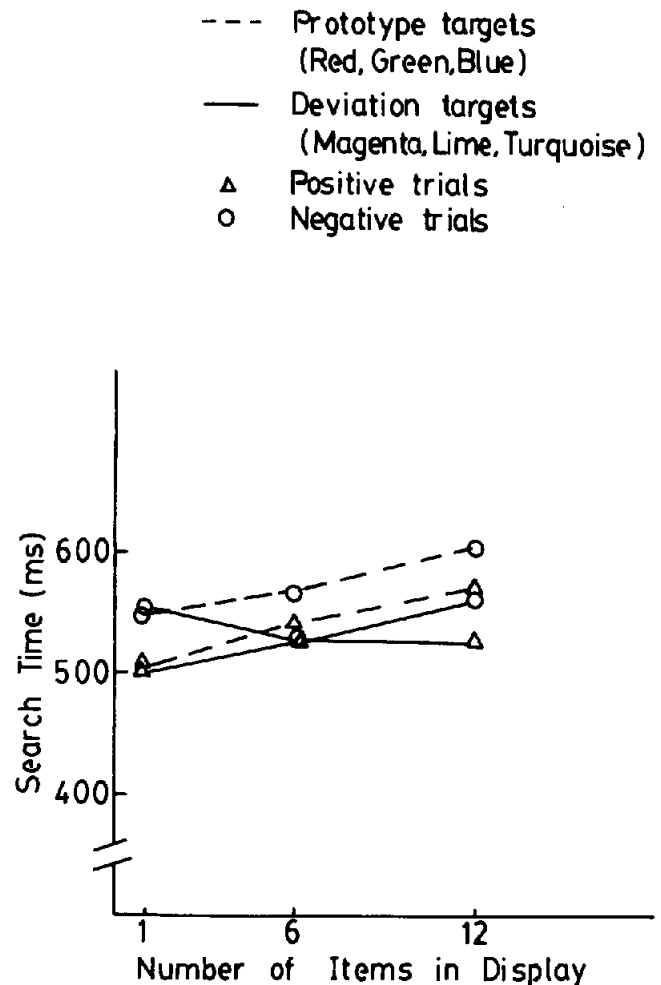


*Figure 8.* Search latencies in Experiment 6—color.

throw light on other dimensions, like curvature and tilt, that also give search asymmetries. Coarse coding is certainly used on the color dimension: Each stimulus value activates more than one channel, and each channel is activated by many different values. However, the prototypical red, green, and blue dots that we used would probably have produced more activity within their own primary channel and less on either neighboring channel than the magenta, lime, and turquoise. A magenta dot would primarily affect the red channel, but it would also produce some activity in the blue channel. Again, we can draw an analogy with the circle-plus-line experiment. Detection of a magenta target might be mediated by the added presence of activity on the blue channel as well as by the shared activity on the red channel. A red target, on the other hand, would produce more activity than magenta on the shared red channel, but against a background level that was already high through the effects of the multiple magenta distractor dots. Figure 9a shows the model we envisage.

This interpretation of the color asymmetry matches the hypothesis we proposed for the curvature and orientation dimensions. It retains the idea that standard values are coded as the absence of activity on the deviating dimensions; but it assumes that they are positively coded on their own channels, with the
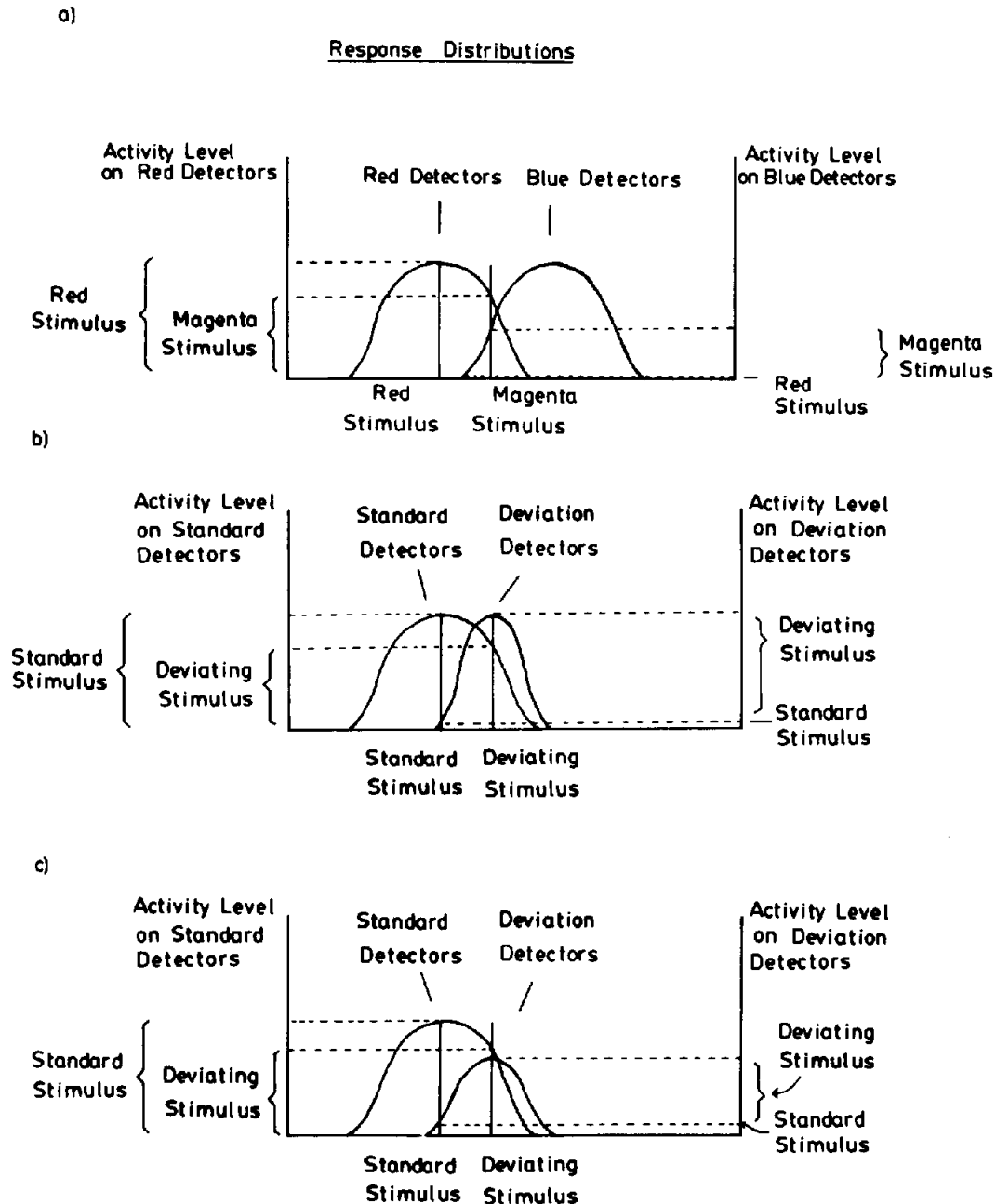
a)

## Response Distributions



b)



c)



*Figure 9.* Possible models for distributions of feature activity in detectors for standard and for deviating values: (a) widely spaced broadly tuned channels, (b) closely spaced detectors with broader tuning for standard than for deviating values, and (c) closely spaced detectors with asymmetric inhibition.

proviso that the deviating stimuli also produce substantial activity in the prototype channel. When the target is a prototype, it activates its own channel more than any individual distractor does, but the increase must be detected against a high background level produced by pooled distractors. When the target is the deviating stimulus, it activates the prototype channel less than the prototype, but in addition it produces activity on another channel on which the prototype distractors produce little or no effect. The asymmetry then follows from Weber's law: Detecting *some* against a background of *none* should be easier

than detecting *more* against a background of *some*. As soon as the stimuli are sufficiently separated for the "deviating" stimulus to produce little activity on the "prototype" channel, the asymmetry should disappear, and we predict pop-out for both, as we found for green and black targets among red distractors (Treisman & Souther, 1985). This model would account for results obtained with stimuli coded by discrete and broadly tuned channels, as is probably the case with color. For deviating stimuli to give a search asymmetry, they must lie closer to the prototype channel than to the nearest neighboring channel.

There are alternative models, shown in Figure 9b and 9c, that would also give rise to the asymmetry in cases where the detectors are not grouped into widely spaced channels and where the deviating stimuli maximally activate their own separate detectors. In each case the hypothesis is that detectors that are maximally sensitive to standard or reference values are more strongly activated by off-standard values than detectors for nonstandard values are by standard values. (Note again that the functional detectors we hypothesize here are not necessarily assumed to be single neural units.) The difference in breadth of tuning could be a permanent property (as in Figure 9b), or it could result from asymmetric inhibition when standard and nonstandard values are both present in the field (as in Figure 9c). Stimuli with the standard value would effectively sharpen the tuning and decrease the response of detectors for nonstandard values more than the reverse. The effect would be a form of assimilation to the norm. The deviating detectors are, or become, more narrowly "tuned," with the effect that they respond very little to the standard stimuli; the deviating stimuli, on the other hand, produce substantial activity in the standard detectors as well as maximally activate their own. Note that fine discrimination (unlike detection) is likely to depend on the ratios of activity in different detectors rather than on the presence or absence of activity in any single detector. Broad tuning with overlapping sensitivities is an asset for discrimination rather than a liability. Thus the model need not predict poor discrimination of pairs of stimuli differing around the standard values—only poor detection of the standard stimuli among deviating distractors.

In summary, all three models suggest that deviating distractors mask the standard target by producing high background activity in detectors for standard values, whereas a deviating target is itself detectable among standard distractors through the additional unique activity it produces in its own narrowly tuned detectors. If we apply these models to curved and straight lines, Model A implies that the curved lines lie closer to the mean of the straightness detectors than to the mean of the nearest curvature detectors. Model B assumes that the detectors for straightness are more broadly tuned than those for curvature and therefore more easily activated by curves than the corresponding curvature detectors are by straight lines. Model C assumes asymmetric inhibition that has stronger effects on the curvature detectors than on the straightness detectors. Foster (1983) reported some interesting psychophysical discontinuities that suggest the existence of discrete populations of detectors for different degrees of curvature.

Applying our models to orientation, we recall that the less detectable target seems to be defined as the frame-aligned target rather than the vertical one. There is evidence for the existence of orientation detectors whose peak sensitivities are separated by less than 18° (Campbell & Maffei, 1970; Hubel & Wiesel, 1965), which makes Model A unlikely. The width of tuning, not the number of cells, is relevant to Models B and C, and here the physiological evidence is unclear. In order to explain the frame-alignment asymmetry, these models would require that the width of tuning or the amount of inhibition be adjustable to match the frame-aligned definition of vertical and horizontal.

The search asymmetry for orientation targets was found only with pairs involving the standard and the one deviating value (aligned vs. misaligned). It was not present with two deviating values (18° and 36° tilt). Both deviating values gave flat search

functions, although the intercept was higher for the less tilted target. The analogy with quantitative dimensions would suggest a coding of perfect alignment as the zero value on the dimension of misalignment, with increasing degrees of misalignment coded as quantitatively increasing values on a single dimension, comparable to increasing contrast or length. The physiological and psychological evidence, however, suggests that different orientations are coded by different detectors—place coding rather than intensity of firing—with each detector responding maximally at a different preferred orientation. One would expect asymmetries on place-coded dimensions only when the values presented are sufficiently close to activate the same detectors to differing degrees, and not when they activate different detectors. Two degrees of tilt that were closer than 18° and 36° might have given an asymmetry. Of course, place coding of this kind may also be used for some quantitative dimensions. Line length seems a plausible candidate, with length perhaps coded initially by hypercomplex receptive fields of different extents. Two line lengths separated by more than an 8:5 ratio might not give any asymmetry. Further research is needed to clarify whether there is a genuine difference between dimensions with standard values and place coding and dimensions with no standard values and with coding by the amount of activity within a single channel.

If we apply the prototype–deviation hypothesis to account for the circle–ellipse asymmetry, the suggestion is that the ellipses activated both the detectors for circularity and the detectors for elongation, whereas the circles produced little effect on elongation detectors, (a) because the ellipses fell between two overlapping detector distributions (perhaps those for spots and those for bars) or (b) because the detectors for circles were more broadly tuned than those for ellipses or (c) inhibited them more strongly.

Can we relate the prototype–deviation asymmetry in search to the asymmetry in similarity judgments noted by Rosch (1975) and by Tversky (1977)? Rosch pointed out that we typically compare an atypical to a prototypical stimulus and that judgments are affected if the direction of comparison is reversed. Pink is compared with true red and is judged more similar to it than the same red is to pink; tilted lines are compared with horizontal or vertical lines and are judged more similar to them than the reverse. Similarly, an ellipse may be compared with and found more similar to a circle than the reverse. Is there a general rule by which, if $A$ is more similar to $B$ than $B$ is to $A$, one can predict the search results for a target $A$ in $B$s or for a target $B$ in $A$s? Asymmetric similarity might then provide an explanation for both. It is not immediately obvious that this would work. We have suggested that moving from a prototype to a deviation is equivalent to adding one or more features (e.g., adding elongation, tilt, or curvature in our experiments) and that moving back from deviation to prototype is equivalent to subtracting or reducing features. A target pops out when it has an additional feature, or much more of a shared feature than the distractors. Rosch's and Tversky's results suggest that similarity is greater both when an included figure is compared with an including figure (e.g., $F$ to $E$) and when a deviating stimulus is compared with a prototype. In the former case, a stimulus with fewer features is compared with a stimulus with more features; however, according to our argument, the prototype has fewer features than the deviation, yet the similarity judgment

goes in the other direction. Some other principle must therefore be invoked to explain the asymmetry in similarity judgments.

Tversky (1977) suggested that *salience* is the critical factor in asymmetries of similarity; if so, it must be in a different sense from the salience that mediates pop-out in early vision. In search, the prototype appears to be less salient than the deviation, whereas Tversky's account of similarity requires the reverse. The pop-out criterion agrees with the similarity criterion that the more complex, or including, figure is more salient than the less complex, or included, figure. Perhaps the addition of a property has an effect that differs from the addition of a part in determining judged similarity but functions in the same way so far as search is concerned.

## Line Arrangements

The next three experiments tested some possible emergent features created by the spatial arrangement of two straight lines. The features we tested were intersection, juncture, and convergence (vs. parallelism). These properties have all been proposed as possible visual primitives in earlier articles. Julesz and Bergen (1983) listed three basic units of preattentive texture perception that they called *textons:* elongated blobs, terminators, and crossings of line segments (intersections). They showed that an area containing pluses (intersecting lines) segregates easily from an area containing separate orthogonal lines in L-shaped arrangements. However, their stimuli may have differed in other simple features: The global and the apparent size of the pluses and the *L*s differed markedly, although the component lines were matched in length; the pluses contained small right angles whose sides were less than half the size of the *L*s; and the intensity distribution at low spatial frequencies also differed. Looking with blurred vision at Julesz and Bergen's displays appears to improve the texture segregation and pop-out, suggesting that it is unlikely to depend on the detection of fine detail. Our aim was to deconfound these variables as far as possible and test whether line intersections are detected in parallel in a search task in which global size, local contrast, and the size of right angles could not be used as additional cues.

Johnson (1978) has discussed the effect of juncture on the detection of component lines. He found that discrimination of diagonal lines from curves or from horizontal and vertical lines was slowed when the diagonal lines met to form an angle or an intersection, as if lines that touch are thereby fused to form a perceptual unit, making the components less accessible. Similarly, Beck (1982) noted that horizontal and vertical lines can be prevented from segregating perceptually when they are joined to form *L*s or *T*s. White and Riggs (1974) reported color aftereffects contingent on an angle's direction of pointing, which they claimed could not be explained simply by the orientation of the component lines. If selective adaptation is taken as evidence for the psychological reality of the features involved, this might suggest that angles form perceptual units to which different colors can be contingently associated.

Finally, Stevens (1978), Witkin and Tenenbaum (1983), and Lowe (1984) have all drawn attention to the significance of both parallel lines and converging lines as cues in the interpretation of three-dimensional structure.

These simple relational properties, then, appear to be plausible candidates to function as visual primitives by the parallel

search test. The next three experiments explored which, if any, would in fact pop out.

### Experiment 8: Intersection

The stimuli were pluses consisting of intersecting horizontal and vertical lines (13 mm in length and subtending 1.8°) and pairs of separate components of the pluses—each pair composed of one 13-mm horizontal or vertical line and one right angle with 6.5-mm sides. Examples are shown in the left panel of Figure 10a. Thus we used lines that matched the lines of the pluses in length without confounding global size differences, and we used right angles that also matched the size of the right angles in the pluses.

### Experiment 9: Juncture

The stimuli were right angles with 9-mm sides, subtending 1.2°, and orthogonal lines separated by 3 mm so that they formed a larger, 12-mm right angle with a gap replacing the 3 mm nearest the point of intersection. The angles and orthogonal lines were placed in haphazardly selected orientations. Examples are shown in the center panel of Figure 10a.

### Experiment 10: Convergence/Parallelism

The stimuli were pairs of parallel 11-mm lines, subtending 1.5° and separated by 4 mm, and pairs of converging 11-mm lines, separated by 6 mm at one end and 2 mm at the other. The pairs of lines were placed in haphazardly selected locations and orientations. Examples are shown in the right-hand panel of Figure 10a.

The search latencies are shown in Figure 10b, each below its relevant display type. None of the tasks appears to allow parallel search. Each showed a significant increase in latency as the number of distractors increased. The rate of serial search was very slow both for the joined lines and for the parallel lines—about the same as for conjunction search with green *T* targets among green *X* and brown *T* distractors (Treisman & Gelade, 1980). Search for the separate lines and for the converging lines was considerably faster than search for the joined or parallel lines. Neither, however, appears to be detected in parallel by the pop-out criterion. The results for intersection conflict with those of Julesz and Bergen (1983), who found easy texture segregation between pluses and *L*s and parallel search for a plus among *L*s. As we suggested earlier, however, their displays may have allowed the use of other, primitive features besides the presence of intersection. We found no evidence that any of these three pairs of line arrangements generates an emergent feature that is preattentively coded (Pomerantz, Sager, & Stoever, 1977; Treisman & Paterson, 1984).

Previous experiments have shown similar failures of parallel detection for *T*s among *L*s (Beck & Ambler, 1972), for *R*s among *P*s and *Q*s and for *T*s among *Z*s and *I*s (Treisman & Gelade, 1980), for arrows among angles and lines (Treisman & Paterson, 1984), and for acute angles among mixed right angles and diagonal lines (Treisman & Souther, 1985). The potential features we have tested so far—intersection, juncture, convergence, acute angles, and arrow vertices—are among the simplest and the most distinctive patterns resulting from possible
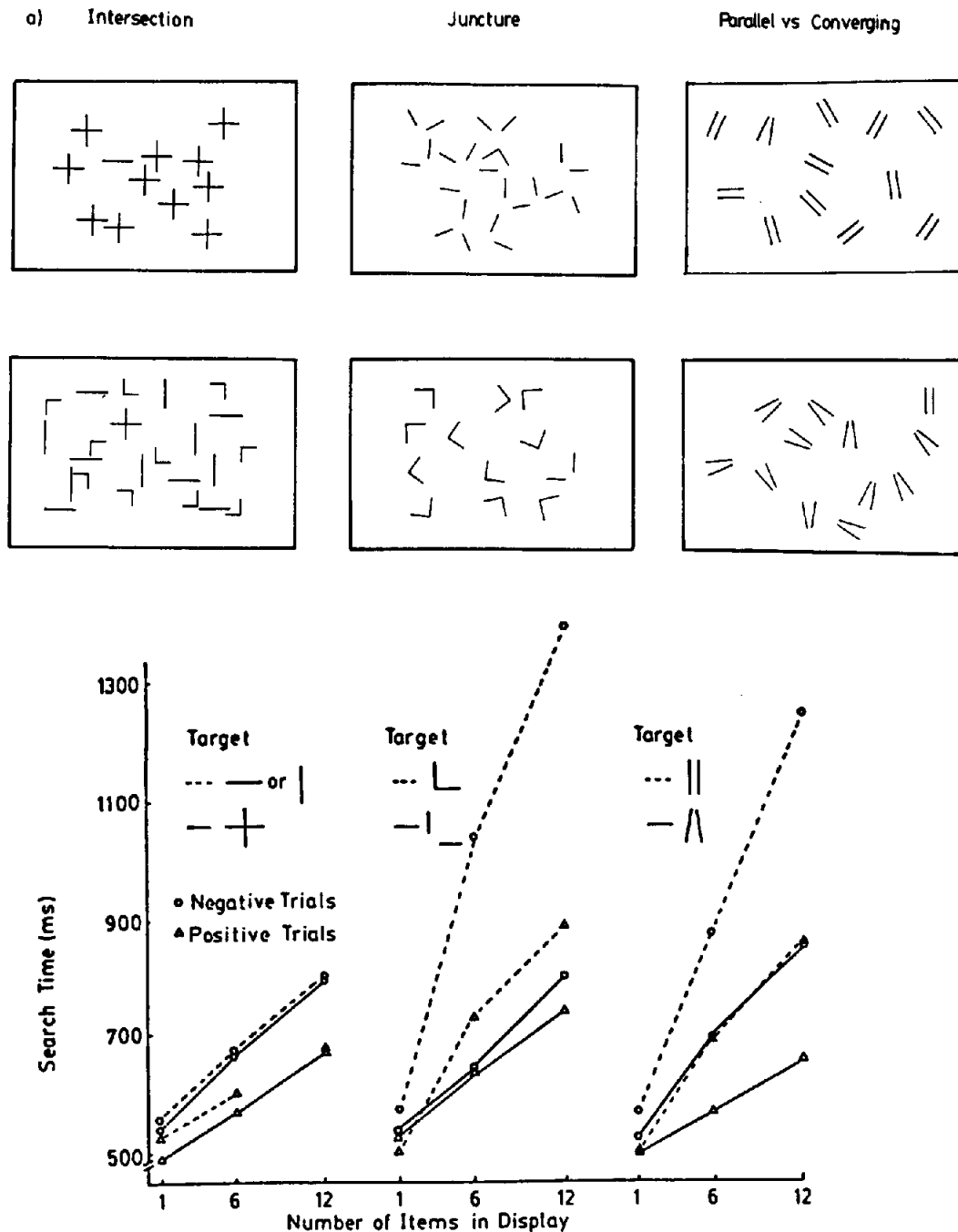
*Figure 10.* (a) Examples of displays testing search for line arrangements and(b) search latencies
in Experiments 8, 9, and 10—intersection, juncture, and convergence.

line arrangements; yet none seems to be categorically coded as
a unique and separable feature by the parallel pop-out test. If
the conclusion can be generalized, it seems important. The sug-
gestion is that no functional feature detectors exist that respond
uniquely to properties of line arrangements, at least at the paral-
lel preattentive levels of early vision. The present experiments
extend the conclusion to cases where it seemed a priori most
likely that emergent features might be created by the relations
between the component lines. The only exception so far re-

ported is the emergent property of triangles among angles and
lines (Pomerantz et al., 1977; Treisman & Paterson, 1984),
where closure appears to mediate preattentive detection. Note
that we distinguish closure from connectedness; connectedness
appears not to be preattentively available (see Experiment 11
and Treisman & Souther, 1985).

In a sense, this negative result is encouraging because it is
consistent with the claim that pop-out taps early levels of visual
analysis. We would be more worried if the number of visual

primitives multiplied to match whatever search task we set the subject. It is possible, however, that new candidates could be added through extended experience and practice in the search task. All the stimuli we used were extremely familiar and simple, but they had not been the subject of intensive practice in the particular search tasks we used. Our subjects were usually tested in one session only; we were testing the visual processing that occurs spontaneously and automatically with simple familiar stimuli. Shiffrin and Schneider (1977), on the other hand, trained pop-out of particular sets of letters (e.g., *K, D,* and *L*) by presenting thousands of search trials with consistent allocation of items to the roles of target and distractors. Eventually their subjects had trouble reading the newspaper because they saw only the *K*s, *D*s, and *L*s. It is important to understand the change that occurs here. If newly established functional feature detectors mediate pop-out for what were previously conjunctions of features, would they also meet the other criteria for preattentive features, such as easy texture segregation and identification without localization? If so, the results would suggest some plasticity in the mechanisms of early vision, even in adults.

Once attention is focused on them, the arrangements of lines become very salient, even without specific practice. Structured relations like intersection, juncture, and convergence may belong to a separate vocabulary of primitives involved in object analysis. They could be identified automatically by discrete, well-established perceptual routines (Ullman, 1984) once attention has been spatially focused on them and then combined and interrelated with other features to form more complex object representations. Here, possible criteria for separability would be the ability to classify objects on the basis of one such property without interference from others and independence in the contribution each property makes both to the judged similarity between objects and to their identification in absolute judgment tasks (Garner, 1974).

Although none of the line arrangement patterns allowed parallel detection, two of them gave rise to search asymmetries, suggesting that target and distractors shared a relevant property to differing degrees: The separate lines were found faster than the joined right angle, and the converging lines were found faster than the parallel lines. The asymmetries discovered in Experiments 1 through 7 suggest that standard values are coded in the same way as lower values on quantitative dimensions and that deviations from a standard are coded in the same way as higher values. Applying these conclusions to the present results, we would infer that juncture is coded as the standard value, giving less activity, and separate lines as deviations, giving additional activity, either in the same or in other functional feature detectors. It is possible that the underlying discrimination of joined versus separate lines is based simply on the number of line ends, four for the separate lines and only two for the angles (cf. Julesz, 1981; Marr, 1976; Treisman & Souther, 1985). Thus more versus less here may actually be a numerical difference in the number of relevant features per item.

Applying the models in Figure 8 to the discrimination of parallel and converging targets, we would infer that the detectors for the standard, or reference, value—parallelism—are activated by both parallel and converging lines, whereas the converging lines also activate detectors for convergence. The absence of any asymmetry with the intersecting lines as well as with the separate lines

and angles makes sense in this framework. It is difficult to see which quantitative or qualitative dimension the two types of stimuli might share to differing degrees.

## Topological Properties: Connectedness and Containment

The last two experiments tested two topological properties—line connectedness and containment (dot inside a boundary)—together with their opposites—line ends (terminators) and exclusion (dot outside a boundary). Ullman (1984) has recently discussed a set of hypothetical visual routines that might serve to identify topological and relational properties relevant to object identification rather than to early texture segregation. Ullman suggested that these routines comprise subsets of basic operations that can be differently combined and ordered to achieve different goals. They are, by their nature, restricted to serial application. The basic operations that he suggested include boundary tracing, counting, bounded activation (or "coloring"), shifting the processing focus, and marking. He gave examples of their application in the perception of inside versus outside relations and in the perception of connectedness. If Ullman was correct, properties whose computation requires visual routines should not be available at the parallel preattentive level, although they might be very salient with focused attention once the routine has been applied. It seemed worthwhile to test this prediction for two examples.

### Experiment 11: Connectedness and Terminators

This experiment was reported by Treisman and Souther (1985). The stimuli were closed circles (subtending 1.5°) and circles with randomly located gaps. We tested three different gap sizes (one eighth, one fourth, and one half the circumference). The results, shown in Figure 11 and in Table 2 were clearcut: The circles with gaps popped out of displays of closed circles, but the closed circles were found only through apparently serial, self-terminating search, the rate of which varied with the size of the gap. The pattern of performance suggests that line ends (terminators) marking the gap are preattentively detected in parallel, regardless of the number of closed circles and regardless of gap size (assuming acuity limits are not exceeded), whereas line connectedness is not. Instead, when the target is a closed circle, the relevant dimension appears to be a continuous one—degree of closure—that is shared to differing degrees by the distractor circles that have gaps. When the difference is large, as with the semicircle distractors, the closed circle is found easily, almost in parallel; when the gaps are small, search is as slow as the typical search for conjunctions (more than 60 ms per item). We suggested that the different search rates reflect search through groups of different sizes, with items within groups checked in parallel to see if their pooled response on the dimension of closure exceeds the criterion for target presence.

An alternative account might be that a visual routine of boundary tracing is applied to each item in turn and that the time taken depends on the length of contour to be traced (one half, three quarters, and seven eighths of the complete circle for the different gap sizes). However, the search rates (13, 34, and 61 ms per item, respectively) did not increase in the predicted proportions, and it seems more parsimonious to account for
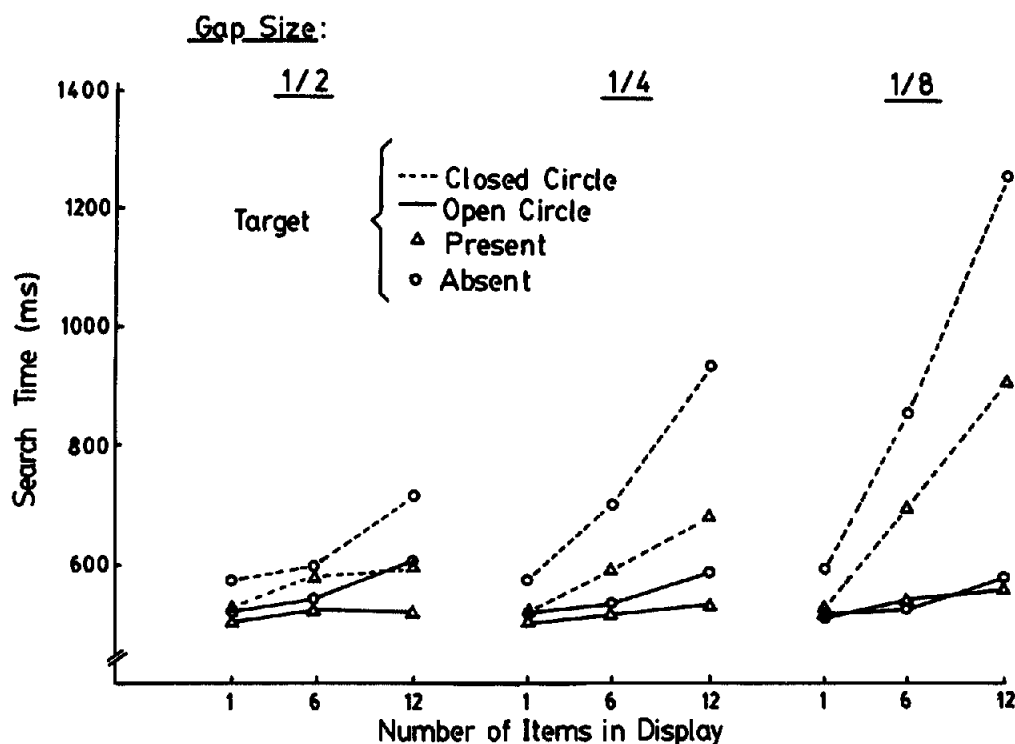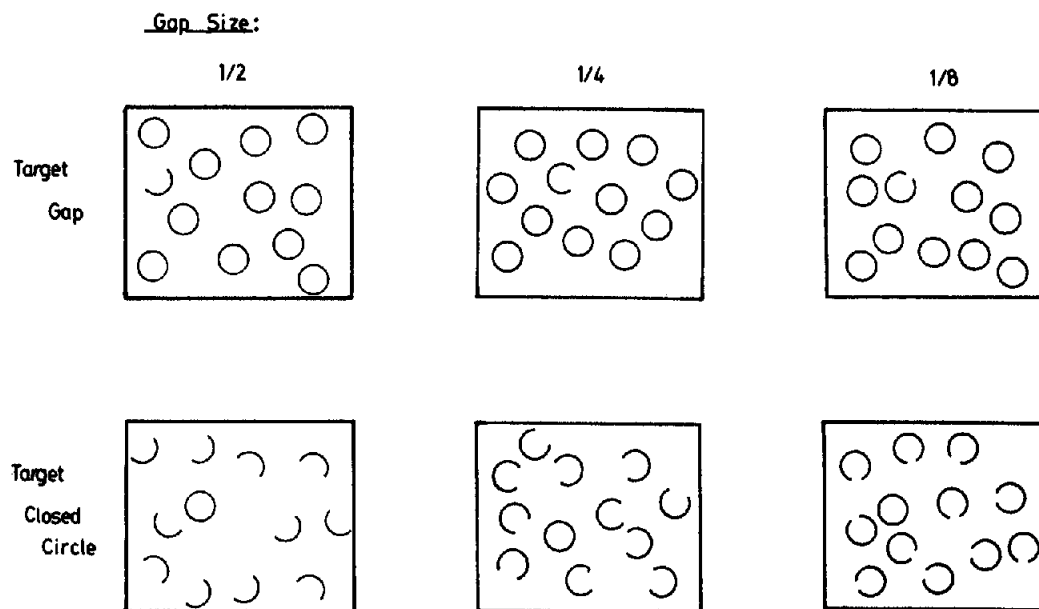
*Figure 11.* (a) Examples of displays testing search for closed circle or circle with gap and
(b) search latencies in Experiment 2—connectedness and terminators.

these closure results within the same framework as those for
curvature, line length, and the other continuously variable
properties tested in our other experiments.

*Experiment 12: Containment (Inside vs. Outside)*

In the final experiment we tested another simple topological
feature: whether a dot was outside a contour or contained

within it. Again, this is a property that, according to Ullman,
requires the use of a visual routine and therefore is likely to
require serial processing. To test the topological property of
containment, we require that it be abstracted from otherwise
varied instantiations. In this experiment, the stimuli were
mixed displays of two different convex container shapes with a
2.5-mm black dot either inside or outside each shape and with

mixed displays of two different concave container shapes, again with 2.5-mm dots either inside or outside. The convex shapes were circles with 11-mm diameters (subtending 1.5°) and rhombuses measuring 8 mm at the narrow end, 11 mm at the wide end, and with 11 mm separating the two ends. The concave shapes were the same figures with a slice removed, leaving an inward pointing angle as part of the contour, making a "Pac-Man" from the circle and an equivalent straight-edged form from the rhombus. The concave angle replaced 0.26 of the circle boundary and the narrow end of the rhombus. The dots were randomly located either inside or outside the contours of the shapes, with mean distances matched, except that with the concave shapes, one fourth of the outside dots were placed in the concave angle. Figure 12a shows examples of each type of display.

The search times are shown in Figure 12b and in Table 2. Serial search appeared to be necessary in both cases. With the four shapes that we used, it seems that early vision supplies no direct coding for the topological property of being inside or outside a boundary, although in a pilot experiment we did get pop-out for a single fixed shape (circle) and a fixed dot position (center) (Treisman, 1985). This bull's-eye pattern may be a special case with an emergent feature that could function as part of a face-recognition system. The present experiments gave very different results with only slightly more complex displays. Concave shapes gave slower search rates than did convex shapes, and the error rates were substantially higher, particularly for trials on which the dot was outside the shape but inside the concavity. Here subjects missed one third of targets for displays of 6 or 12 items, presumably coding them as if they were inside dots like those in the distractor shapes. The difference between concave and convex shapes disappeared on positive trials in which the target dot was outside the shape and not in the concavity (averaging 8.7 ms per item for concave shapes compared with 7.9 ms for convex shapes). This suggests that the feature that subjects attempt to detect for outside targets is an isolated or noncontained dot. When the concavity partially surrounds the dot, it obscures the relevant feature and leads to slow search and high error rates. It also induces caution and double-checking before a negative decision is made on trials where no isolated outside dot is found, producing an unusually high ratio of negative to positive slopes. When the target was an inside dot, one quarter of the concave distractor shapes had an outside dot that was partially contained by the concavity. If subjects searched for the one shape without an outside dot, one would expect performance also to be slower and more error-prone with concave than with convex shapes.

In both experiments, there was a significant search asymmetry giving steeper slopes for the inside dot target than for the outside dot. This is consistent with the idea that the relevant feature is the noncontained dot. The direction of the asymmetry is surprising, however, in relation to possible visual routines proposed by Ullman to detect containment. The coloring method, for example, would require some form of activation to spread from the dot until it reached a boundary or, for container shapes of known size (as in our experiment), until it exceeded the maximum possible distance. If no boundary is reached in at least one direction, one can assume that the point is not contained; if it is stopped in all directions, the point must be con-

tained. This routine should generate shorter decision times when the point is contained than when it is not, because the latter can be recognized only by default. Containment should, therefore, be the feature that subjects choose to code. Similar arguments apply to the ray-intersection method in which a ray is drawn from the point in question out to infinity (or to a known maximum distance), and the number of intersections it makes is counted. An odd number implies that the point is contained, and an even number implies that it is not. It is difficult to see how either routine could code outside dots faster than inside dots. The fact that partial enclosure in the concavity makes the outside targets so difficult to detect suggests that the relevant feature, as coded by the visual system, relates either to the amount of contour-free space around the outside dot at the distances where the shape boundaries would be expected if the dot were contained, or to the shape of the nearest contour—whether it is concave around the dot or convex. Whatever the specific nature of the cue, it certainly involves the coding of spatial relationships and seems not to be preattentively available as an emergent property.

Note, however, one unusual aspect of the results: namely, the crossover in the search functions separating latencies with displays of 1 item from those with displays of 6 and 12. With a single stimulus, the response was faster for inside than for outside dots. This is the only experiment in which a crossover was obtained. A possible interpretation of the crossover effect is that subjects code some property of the target in single-item displays and some property of the distractors in multi-item displays. Ullman's suggested routines favoring the inside dot would then be consistent with our results. When looking for an outside dot in multi-item displays, subjects would check instead that each distractor has an inside dot and therefore rule it out as the target.

To test this hypothesis we ran a supplementary experiment (Experiment 12a) in which we replicated the outside target condition with convex shapes, both with the outside dot present (as before) and with no outside dot to mark the target. When no outside dot was present, subjects were forced to search for an empty shape. In both conditions, however, the distractors were the same shapes with inside dots. If performance depended on checking the presence of the inside dots in the distractors, both should give the same search functions. In fact, search proved to be significantly slower when no outside dot was present, averaging 15.6 ms per item on positive trials and 39.7 ms on negative trials, compared with 7.1 and 17.3 ms per item when the outside dot was present. Search for the empty shape contrasting with shapes containing dots gave much the same results as search for an empty circle contrasting with circles with intersecting lines (Treisman & Souther, 1985), which averaged 19.7 and 38.9 ms per item for positive and negative trials, respectively. Once more, the results conflict with the hypothesis that subjects code a property of the distractors rather than a property of the target, even in this experiment in which we obtained the crossover effect between single-item and multi-item displays. Some other explanation is needed for the relative speed with which subjects responded to the single target with an inside dot. Perhaps Ullman's routines are easy to apply to a single-item display but take much longer with multi-item displays because each item must be tested individually. Subjects therefore find some other
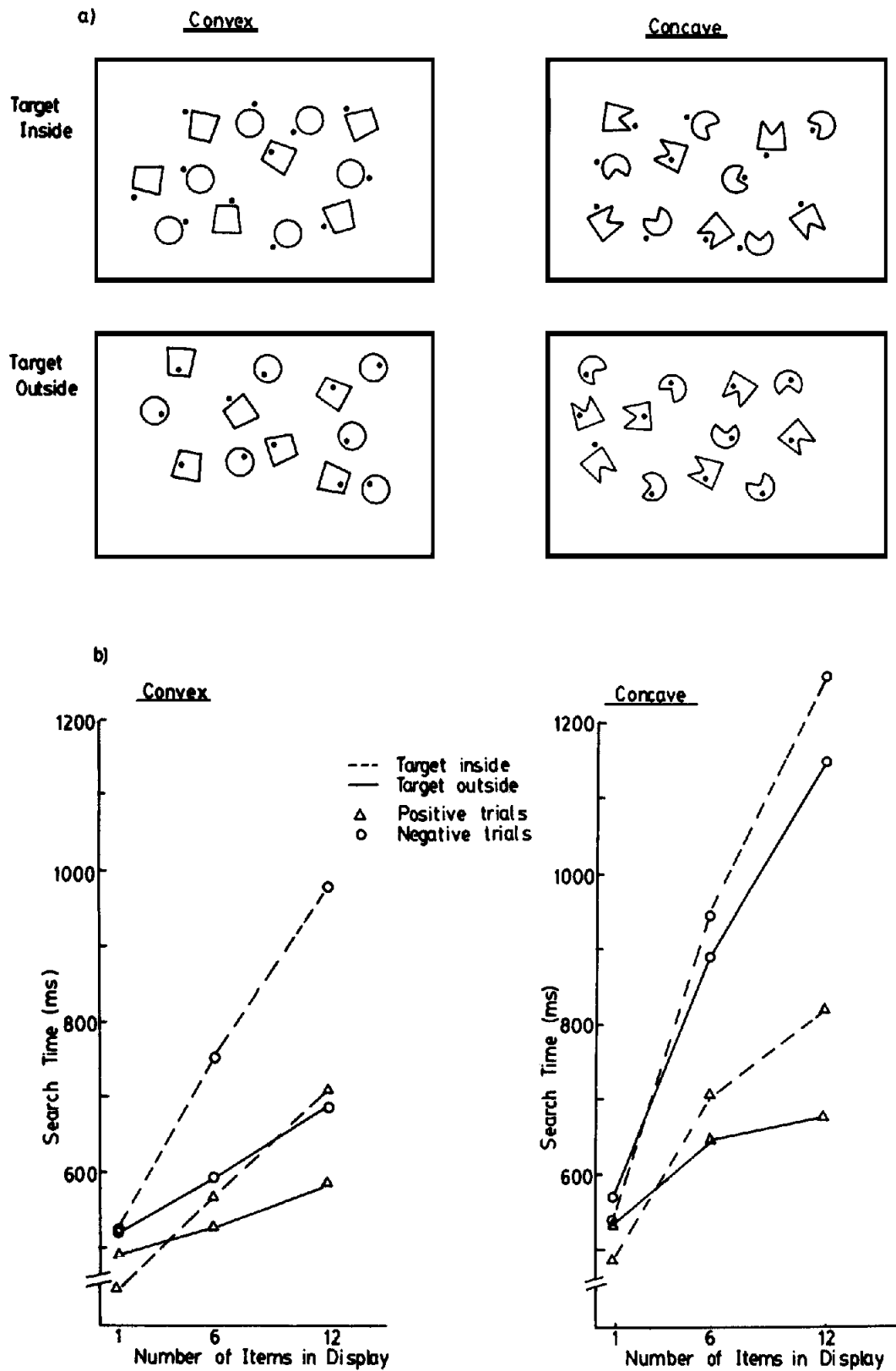
*Figure 12.* (a) Examples of displays testing search for inside or outside dots
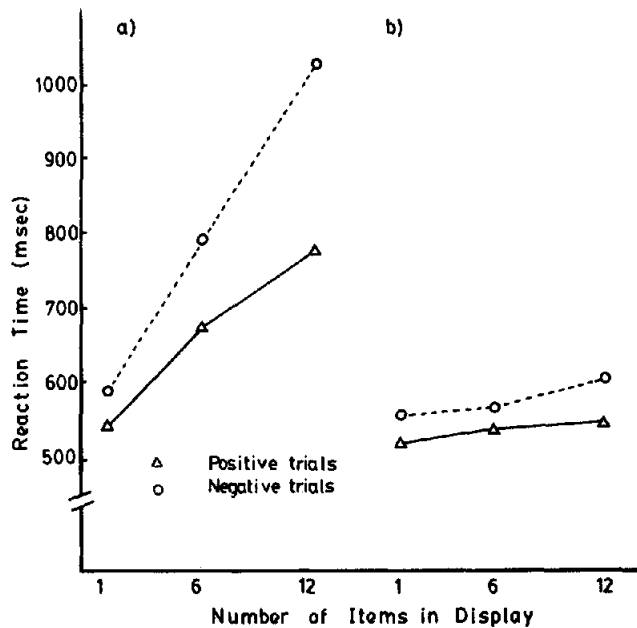and (b) search latencies in Experiment 12—containment.

Figure 13. (a) Mean search latencies in 37 conditions giving slopes above 10 ms per item. (b) Mean search latencies in 17 conditions giving slopes of less than 10 ms per item.

way of coding the outside dots that may be slower for single items but that allows the use of grouping and the pooled response strategy.

## Evidence for Serial Search

In the present series of experiments, we have provisionally interpreted any search function that increased substantially with display size as implying a serial scan, either of single items or of groups of items. This assumption needs to be checked. How strong, in fact, is the evidence to support the suggestion that search is serial when distractors are homogeneous and differ from the target only in degree on a shared dimension? Although one can devise parallel models that mimic serial processing (Townsend, 1972), we take reaction time functions that increase linearly with display size as prima facie evidence of serial search. Ratios of positive to negative slopes that approximate 0.5 suggest that the search is self-terminating. We accept, however, that converging evidence from a number of other tasks is necessary to support these inferences (Treisman & Gelade, 1980).

The grand means for the 37 conditions with slopes greater than 10 ms per item are shown in Figure 13a; the remaining 17 conditions (which gave apparently parallel search) are shown in Figure 13b. The 37 experiments clearly give mean functions that are very close to linear (the negative trials almost perfectly so), suggesting that the slight deviations in different experiments were mostly due to noisy data. The proportion of the variance with display size that was due to linearity was .987 for the positives and .9998 for the negatives. We checked separately whether departures from linearity contributed significantly to the variance due to display size in any of the 37 experiments for which the mean slope was at least 10 ms per item. Departures from

linearity in the variance due to display size were significant only on positive trials with circle targets among distractor ellipses: for fixed orientation, $F(2, 14) = 3.9$, $p < .05$, and for varied orientation distractors, $F(2, 14) = 8.8$, $p < .01$. This may be an artifact attributable to the particular selection of displays we used, or it may be a real effect requiring further research to yield an explanation. No other experiment gave consistent evidence of nonlinearity. In the median of the 37 experiments, the linear component accounted for between 99% and 100% of the variance that was due to display size both for positives and for negatives. Only 6 of the 37 conditions had values lower than 90% for the positive trials (only 2 lower than 86%), and none had values lower than 90% for the negative trials.

The ratio of positive to negative slopes averaged 0.53 across the 37 experiments. This is very close to the ratio of 1:2 predicted by serial self-terminating models. All except three ratios (one juncture and two line-orientation conditions) fell between 0.30 and 0.70. Although not conclusive, the results for almost all the features tested are consistent with the inference that search through homogeneous distractors for a target that differs from them only slightly on a single shared dimension involves a serial, self-terminating scan of items or groups.

## Role of Eye Movements

A final possibility to consider is that the apparently serial scan reflects successive eye movements and fixations rather than serial focusing of attention. No attempt was made in the experiments already reported to control eye movements. With search times that usually exceeded 500 ms, it is very likely that more than one fixation was made before the response was selected. A critical test is to compare search rates when eye movements are ruled out by brief presentations. To avoid unacceptably high error rates, only small displays could be tested. We compared search for a shorter line among longer lines in displays of one to six items when exposure durations were limited to 180 ms and when they continued until the response was selected (as in all our previous experiments). In this experiment, the displays were computer generated on an IBM PC and shown in white on a dark background on a Mitsubishi color monitor. A key-press response was used. The distractors were 8-mm lines, subtending 0.46°, and the targets were 6-mm lines, subtending 0.34° at a viewing distance of 100 cm. The distractors were presented in a 47 × 47-mm area, subtending 2.7° × 2.7°. Displays of one, two, three, four, and six items were tested, with each subject contributing 36 responses at each display size with the target present and 36 with it absent.

Figure 14a shows the results for 8 subjects (6 women and 2 men) who managed to keep their error rates below 33% in all conditions. An additional 6 subjects were discarded because they were unable to perform the task with a brief display at this level of accuracy. There was a highly significant effect of display size on search latencies with the brief exposure, $F(4, 28) = 12.39$, $p < .0001$, averaging 20.1 ms per item on positive trials and 35.8 ms per item on negative trials. However, the slopes were significantly lower than with the unlimited exposure, $F(4, 28) = 5.22$, $p < .003$, where they averaged 27.3 and 58.2, respectively. A number of explanations for the difference are possible: The latencies with unlimited exposure might include some eye-movement time or some rechecking time, or the search times
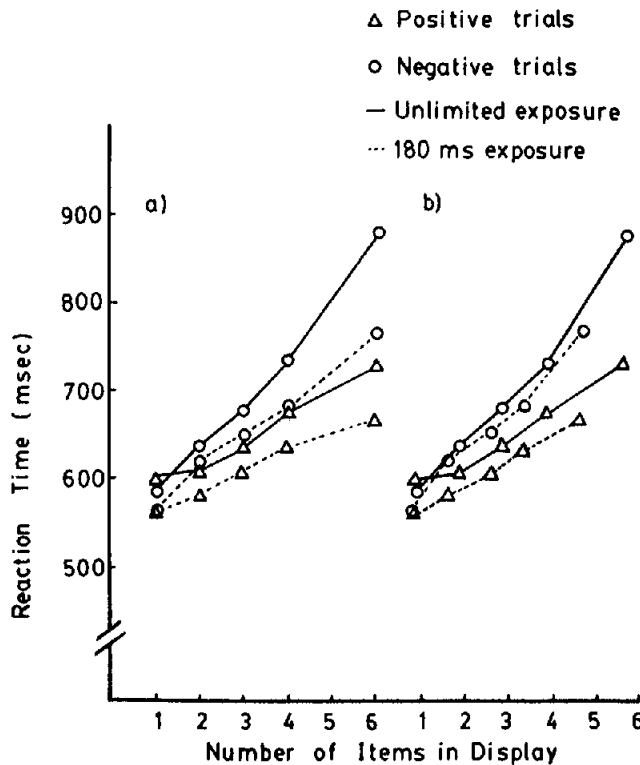
Figure 14. (a) Mean search latencies for line length targets in experiments with brief exposures and with response-terminated exposures and (b) same latencies as a function of corrected display sizes.

with limited exposure might have been curtailed because the display disappeared before all items could be checked. To test this last possibility, we made the assumption that subjects who missed 23% of targets with displays of six items were able to check on average only 77% of the display—that is, 4.62 items. Similarly, the fact that 17% of the targets were missed with displays of four items suggests that on average only 83% of the items were checked—3.32 items. Figure 13b shows the graphs replotted against display sizes corrected in this way for the mean proportions of targets missed in each condition. The difference in slopes has almost disappeared with this correction, suggesting that curtailed processing contributes more to the reduced slopes than the elimination of eye movements.

We conclude that the linear functions cannot be explained by eye movements; these certainly occur when the display remains visible, but our results suggest either that they are controlled in parallel with the internal search, which continues uninterrupted by the external shifts, or at most that they add a small amount to the slopes. Foveation may facilitate the discrimination and reduce error rates in cases where acuity would otherwise be a limiting factor. But our results suggest that eye movements cannot be the only, or even the main, factor determining the increasing, apparently serial functions in search.

## General Discussion

A basic assumption, with which our data are consistent, is that early vision is analytic; it decomposes stimuli along a num-

ber of dimensions and into a number of separable components. In visual search tasks, we suggest that pop-out occurs when the target has a unique feature, which is coded early in visual processing and which is not shared by the distractors. The features may either be discrete and categorical elements (e.g., terminators) that can be only present or absent, or they may be values on a continuous dimension that activate nonoverlapping populations of functional detectors and that therefore also mediate categorical discriminations.

We reported a series of search experiments whose results may help to diagnose some of the functional features coded early in visual processing. We should emphasize, however, that no search task allows direct inference to the complete code for a particular stimulus in any absolute sense. In every case, we tested discrimination between the target and a set of distractors, and we assumed that our behavioral measures reflected the coding of whatever feature (or features) distinguished the target from the distractors. Responses to a circle were based on one feature when it was contrasted with ellipses, on another when it contrasted with circles containing dots or with intersecting lines, and on yet another if it contrasted in size or color with other circles. Whether all these codes are activated whenever a circle is seen, regardless of the task, is an open question. Feature analysis seems to take place automatically on many perceptual dimensions; we normally become aware of the color and length of lines when discriminating their orientation and of the size and shape of the dots when discriminating their contrast. However, there is some evidence suggesting that the results of processing different features are not immediately accessible in parallel to control task responses. Subjects respond a little faster to the presence of a target if they know in advance whether a difference in color or a difference in shape will distinguish it from the distractors (Treisman, 1982).

### Summary of Conclusions About Specific Features

Each set of data has already been discussed in some detail together with the details of the experiment. Here we will simply summarize the conclusions. The evidence from search latencies in this and earlier articles suggests that values on the following dimensions may function as primitives in the language of early vision: colors and different levels of contrast (when sufficiently distinct), line curvature, line tilt or misalignment, and quantitative values like length and number or proximity (again only when the differences are sufficiently large). Terminators and closure (a wholly or largely surrounded area among clearly open shapes like right angles) also meet the criterion for separable features. Nakayama and Silverman (1986) have recently shown that both the direction of movement and stereoscopic disparity can mediate parallel search and therefore should appear on the list of visual primitives. Further research is needed to determine whether these dimensions are those of the retinal image or whether they have been transformed through the operation of perceptual constancy to reflect properties of the external objects. Our experiments do not distinguish these possibilities. Beck (1975) and Gillam and McGrath (1979) reported data from texture-segregation tasks suggesting that both may contribute, at least for line orientations and tilt in depth.

It is interesting that none of the following features met the parallel search criterion: the properties of line arrangements

(intersection, juncture, angles), topological properties like connectedness and containment, and relational properties like height-to-width ratio (although a more extreme difference between spots and bars of equal area might do so). These properties may belong to a higher level vocabulary of shape or object-defining features available only through focused attention.

Some qualitative dimensions appear to be asymmetrically coded, with one direction giving faster target detection than the other. Dimensions showing this pattern include curvature, tilt, elongation (of shape), and convergence (of lines). It would be interesting to know whether movement and stereopsis are also coded with reference to a standard value (stationary for movement and the fixation plane for stereopsis). If they are, we predict that they should also give rise to search asymmetries. In many cases, the value that fails to pop out may be the one that is assumed as a default value because in the real world it is more likely to be the real property of an object. Any departures in viewing angle from the frontal plane will introduce convergence in the retinal image of objectively parallel lines and turn circles into ellipses. It would be adaptive, then, to allow broader tuning for the values that are likely to identify the true object. On the other hand, deviations from these values in the retinal image would carry important information about the viewing conditions, which should be accurately coded to ensure efficient behavioral interaction with the object.

## Coding Feature Values or Differences

So far in discussing possible functional features we have assumed that each item gets a visual code of some kind. However, in any display containing at least two different stimuli, two forms of coding are possible: (a) The different values on the dimension along which the presented stimuli produce mutually exclusive codes can be identified, so that each item generates a separate code labeling its particular value. (b) Alternatively, the differences or contrasts between the items might be directly coded as such (Beck et al., 1983; Mayhew & Frisby, 1978; Sagi & Julesz, 1987). At locations where adjacent items differ, the relation between them may activate specialized difference detectors. Each local boundary would then give a single code for its identity, labeling the relation between the stimuli on either side rather than labeling each stimulus separately. Examples of such relational codes might be *darker than* or *bluer than* or *parallel* (for lines) instead of item codes like *dark grey, blue,* and *vertical.*

It seems likely that the visual system uses both kinds of code. Both the nature and the positions of boundaries and the properties of the surfaces between those boundaries are important in specifying the visual world. Some dimensions may be more relevant to defining surfaces and some to defining edges; thus a relational code may be dominant for some dimensions and an absolute code for others. In displays consisting of discrete elements (like those we used), the density of the elements may also affect which code is used; dense elements would facilitate coding of local contrasts and of emergent features, whereas sparse elements might be individually labeled. Sagi and Julesz (1987) suggested that preattentive processing is parallel only for dense displays (interitem distance less than two-item widths); their results were obtained using line orientation as the relevant feature. On the other hand, Jenkins and Cole (1982) found im-

paired performance in detecting luminance targets as density increased and found no effect on targets defined by size. Nothdurft (1985) has shown clear differences in the ease of texture segregation (the detection of global boundaries) depending on the ratio of element size to interelement spacing for both luminance and line-orientation differences. However, he failed to find striate cells responsive specifically to texture boundaries (i.e., to differences in elements) as opposed to boundaries defined by luminance differences (Nothdurft & Li, 1985).

A simple test to distinguish direct coding of boundaries in texture segregation from separate coding of the items on either side is simply to cover the boundary and a strip on either side and to observe whether the perceptual segregation disappears. Mayhew and Frisby (1978) showed that masking the boundary wiped out segmentation for some textures that differed in their spatial frequencies.

Search tasks offer a further diagnostic to distinguish coding of local relations from coding of individual items. Relational coding would be implied if performance with displays of a single item were slower or less accurate than performance with multi-item displays. Only three conditions that we tested gave any indication that local contrasts between adjacent distractors mediated performance. Displays of one item gave significantly longer latencies than displays of more than one in search for grey targets in the easier condition, in search for deviating color targets on trials when they were in fact absent from the display, and in search for tilted lines among other, less tilted lines. Color and contrast are dimensions that characterize points; their distribution through space defines the elements (such as lines, edges, and areas) to which other properties like curvature, orientation, and movement apply. It may therefore be useful to code directly the boundaries they define as differences as well as identify the particular color or contrast characterizing each area. We have already suggested that tilted lines differing in orientation may generate an emergent property of line convergence when displays are sufficiently dense. For all the other dimensions that we tested, responses to displays of 1 (requiring absolute judgments) were faster than (or equal to) responses to displays of 6 or 12, and most gave times that fit well on a linear function with displays of 6 and 12. Further research, varying density independently of display size, is needed to test the generality of this conclusion.

## Search Asymmetry

We proposed that search asymmetries arise when a single feature in which target and distractors differ is present in one of the two and absent or reduced in the other. This hypothesis covers a number of different cases: (a) search for targets defined by an added component or part (e.g., the circle with an intersecting line among circles without); (b) search for targets with a categorical feature that can be only present or absent (e.g., the line ends of a circle with a gap among closed circles); (c) search for targets with more of a quantitative property among distractors with less (e.g., longer lines among shorter lines or darker greys among lighter greys); and (d) search for targets that deviate from a standard or reference value among distractors that do not (e.g., curved lines among straight ones or ellipses among circles). Here we suggest that the deviating stimuli are distinguished from the standards by the additional activity they generate in

detectors for a positively coded dimension of deviation from the standard (e.g., curvature or elongation against a background of shared activity in detectors for straight lines or for circles).

If the relevant contrast is between the presence and the absence of activity in a population of feature detectors, the search task gives pop-out when the feature is present in the target and serial search when the target lacks it. If the contrast is between more and less of a shared property, search is serial in both cases, but it has a flatter slope when the target has more of the property than the distractors. Our choice of this hypothesis rather than the alternative (i.e., that search is parallel when the relevant feature is present in the distractors and absent from the target) rests on four pieces of evidence. First, in our initial test, we found that adding a local component (a line) to define the target produced pop-out, whereas subtracting it from the target among distractors that all possessed the component led to serial search (Treisman & Souther, 1985, Experiment 1). This is the most direct evidence that feature presence is critical for the target and not for the distractors, because i involved the physical addition or removal of a component. Whatever the relevant features of the added line were, they were all removed when the line was absent and added when it was present. A similar conclusion is implied by the control experiment (12a) on containment/exclusion, which revealed less efficient search for an empty target when the outside dot was removed. Second, the experiments with quantitative dimensions extended this conclusion by linking faster search to conditions in which the target had more extreme values than the distractors did. Third, Experiment 5d with line orientation confirmed that target rather than distractor properties are critical by showing that only the frame-aligned target was hard to find, whereas misaligned as well as aligned distractors allowed parallel search. Finally, distractor heterogeneity of shape had no effect on search rates when the target had a unique feature (an intersecting line), although it slowed search when the target had no unique feature (Treisman & Souther, 1985). This suggests that the distractors affect search only when the target fails to pop-out.

### Related Research

Superficially, the search asymmetry we have described is reminiscent of the marked difference in difficulty described by Neisser (1963) between search through rows of letters for the presence of a particular target letter and search for a row that did not contain the target letter among rows that did. In this case, too, search for absence is much slower than search for presence. Krueger and Shapiro (1980) suggested that the difference is due to the greater opportunity for misses than for false positives. Search for absence requires the detection of a target in every row, making the risk of missing targets much greater than in search for presence. Neisser's letter-search task differs from ours, however, in that the distractors are heterogeneous; the row without a target in search for absence can take many different forms and can be defined only by default (e.g., "does not contain an *E*"). In our experiments, both the distractors in search for presence and the target in search for absence are equally unique and well-defined (e.g., a straight line among curved lines, a closed circle among open circles). It is an empirical finding that subjects detect one of the pair less efficiently than the other, not a logical difference in the way the tasks are

defined. We "discover" what counts as presence and what counts as absence; for example, in search for an open circle, subjects might have searched for the absence of closure with its attendant high risk of missing closure in each of the many distractors. But in fact this task was easy and almost unaffected by display size, suggesting that subjects actually searched for the presence of free ends, or terminators.

More closely related may be the finding by Frith (1974) and by Richards and Reicher (1978) that a mirror-imaged or inverted or mutilated letter is found more easily among normal letters than the reverse. In our earlier article (Treisman & Souther, 1985) we argued that their effect might be different from ours because search appeared to be serial for both unfamiliar and for familiar letters. The asymmetry could therefore be attributed to the greater speed with which familiar distractors were encoded and rejected. Now, however, we too have found many cases in which both versions of a task appear to be serial, even with simple stimuli, and we have attributed the different slopes to differences in the Weber fraction. The unfamiliar letter effect suggests an extension of our general framework to higher levels of coding at which deviations from learned standards are also signaled positively. Inverted, mutilated, or mirror-imaged letters would be signaled by their normal labels plus the extra feature specifying the presence of a deviation, with or without a specification of its nature.

It may be illuminating to generalize even further from our present tasks and relate the asymmetry in visual search to a well-known finding in the literature on discrimination learning in animals—the so-called feature-positive effect (Jenkins & Sainsbury, 1970). It is much easier to train an animal to approach the stimulus that has a critical feature than to approach the stimulus that lacks it. Similarly, human subjects in a sequential matching task detected a change more easily when a feature was added to the second stimulus than when it was deleted (Agostinelli, Sherman, Fazio, & Hearst, 1986). The stimuli here were line drawings of familiar objects, such as a car with bumpers added or removed; thus the features were natural codable parts of the object. Attaching a behavioral response to a positively coded feature may be the only possible, or at least the only natural, form of learning. Attaching responses to its absence may involve search for some alternative feature that emerges from the absence of the first (e.g., *baldness* might be a positive code for the absence of hair).

It would be interesting to see whether the same asymmetry is present in successive matching tasks with the much simpler stimuli that we used, such as a straight line and a curve or a closed and an open circle. If we look at performance with displays of only one item in our search experiments, we do find that nearly all of them give faster reaction times when the "deviating" stimulus is the target. Thus the asymmetry favoring deviation over standard stimuli is not confined to multi-item displays. Whether the asymmetry would extend to learning and memory tasks is an open question. It may be that the features coded in memory form a different vocabulary, quite separate from the primitives of early vision that determine ease of detection in search. Whether or not the two vocabularies coincide, the asymmetry in discrimination and matching tasks, now that it has been clearly established, could also be used as a diagnostic for identifying the psychologically real components of memory traces in cases where these are not immediately obvious. Is hair

actually a positively coded feature, or is baldness? Finally, both the search diagnostic and the feature-positive effect in matching could be extended to the semantic domain by using words as stimuli. One would predict, for example, that if concepts are stored as sets of semantic components, a nonanimal should be harder to find in search among distractor animals than an animal among nonanimals. Lawrence (1971) reported results consistent with this prediction. Another semantic implication might be that a change from the unmarked to the marked end of a semantic dimension would be more easily detected than the reverse. This would follow if the marked end is thought to be represented as the general form plus an added feature. For example, "tall" can refer simply to the dimension of height ("How tall is he?") without specifying which end, whereas "short" must mean "height" plus the specification "below the mean."

## Relation to Feature-Integration Theory

A new departure from earlier accounts is our current emphasis on the role of attention in ensuring the accuracy of feature information in multi-item displays with low discriminability as well as in ensuring the accuracy of conjunctions. Earlier articles focused on the need to localize features in order to conjoin them with other features. We retain the belief that a target with a unique feature, not shared at all by the distractors, can be detected equally well with and without focused attention. However, the present research suggests that selective attention will also allow finer discriminations between stimuli that share the same feature to differing degrees. If responses to the relevant feature are pooled within the selected area, it follows that the more narrowly focused the attention spotlight, the finer the possible discrimination of feature differences. In such cases, we attribute the need for serial search to the fact that the target simply adds to or subtracts from the pooled feature activity generated by the distractors, rather than uniquely activating a set of detectors for the relevant property. Both shared feature and conjunction targets require serial search because of the need to limit the activity produced in relevant feature detectors to that produced by a single selected stimulus or group. With feature search, the need arises to increase the signal-to-noise ratio when discriminability is low; with conjunction search, the need arises to remove the risk of illusory conjunctions.

Our present hypothesis departs from the account of feature search given in Treisman and Gelade (1980). In that article we claimed that search for feature targets should not give linear functions, implying serial item-by-item analysis, although there might be nonlinear effects of distractor density. We tested subjects in search for target ellipses among larger and smaller ellipses and obtained nonlinear, but steeply increasing, functions. We argued that acuity limits could induce serial fixations, placing more items within foveal vision with the more densely packed displays, thereby giving negatively accelerated search times even though processing remained parallel within each fixation. The experiments differed from the present series in one important respect: They included two sets of distractors, differing from the target on the same dimension but in opposite directions. Thus the targets had to be distinguished both from larger and from smaller ellipses. To reconcile the findings with our present hypotheses, we note that if a group-scanning strategy were adopted, subjects would have to pool separately over small and large items. This could make the increase in latency less steep with the larger displays, because the chance of being able to group adjacent distractors of the same size would increase with display density. Thus, when distractors are heterogeneous on the relevant dimension, particularly if they differ from the target in opposite directions, the grouping strategy will not be equally applicable to all display sizes, and search will give increasing, but not necessarily linear, functions.

## Attention and Localization in Search for Feature Targets

In the original feature-integration proposals (Treisman & Gelade, 1980), we accepted the idea of a dichotomy between preattentive and attentive processing (Neisser, 1967), although we allowed the possibility that attention could be spread over subgroups of items rather than always scanning one item at a time (cf. Eriksen & Hoffman, 1972; Kahneman, 1973). Several experiments on conjunction search have in fact demonstrated serial scanning of homogeneous subgroups rather than single items (Treisman, 1982). The present research brings the group-processing hypothesis into the foreground, and as a consequence blurs the original sharp dichotomy between preattentive and attentive processing. The relation we envisage needs some clarification.

Taken literally, the term *preattentive* means *before* attention operates. But it is often assumed that some tasks directly and only reflect preattentive processing. For example, Neisser (1967) suggested that it guides our navigation around a room or down the street; the outputs of early analysis are fed directly to control some forms of motor behavior. Similarly, some search tasks might be performed preattentively, so that the detection response bypasses the central systems concerned with object identification. This is one possibility. However, there is another, which we prefer: We suggest that voluntary responses in all search tasks depend on the same processing levels that also result in conscious awareness. So-called preattentive search is really search in which attention is distributed widely over the whole display rather than narrowly focused and directed serially to one object or subgroup at a time. The breadth of attention determines how accurately localized an item is and how accurately conjoined its features are. Within the focus of attention, activation is pooled for each feature map, giving an average measure of the degree to which each feature is present in the currently attended elements. Thus attentive processing varies along a continuum from completely divided attention spread over the display as a whole to sharply focused attention to one item at a time. Between these extremes, the attention "spotlight" can be set at varying intermediate sizes.

There are two situations in which it would make sense to vary the size of the attended area. One is illustrated by the search tasks we have studied in this article, where time pressure encourages scanning of groups rather than single items whenever this is possible without excessive errors. Another, perhaps more common, situation is to attend to global objects or to global properties of the display. Thus texture segregation will typically depend on divided attention to whole areas of homogeneous elements in order to locate their boundaries. The local properties will in those conditions be pooled across the attended area; for example, a global area might be seen to contain mostly red elements with a patch of green, but the green could be located

within the red only by narrowing attention to exclude some or all of the red. Prinzmetal (1981) has demonstrated that illusory conjunctions of lines occur more frequently *within* globally defined perceptual groups than *between* them. Some properties emerge only as relations between local elements; examples are the colinearity of local elements or the separation between the eyes that helps to identify individual faces. To identify the orientation or shape of global areas, or to extract relations between local elements, attention would again be spread over a large part of the display. A number of researchers have shown limits to our ability to attend simultaneously to global and to local objects (e.g., Navon, 1977; Ward, 1982), as would follow from our theory.

How then do we envisage the relation between visual processing, responses in search tasks, and conscious experience? If a unique feature defines the target in a search task, its presence will be detected rapidly and will call attention to its location through the link from its feature map to the master map as shown in Figure 1. If the presentation is long enough for attention to narrow down accurately to exclude distractor items, the other features of the target will be correctly selected and conjoined with it, and its location will be available. We assume that conjoined object representations are the only source of conscious experience and of voluntary, instrumental responses (Marcel, 1983; Treisman & Schmidt, 1982). However, if the presentation is too brief, attention may not be focused quickly enough, and the defining feature of the target may be seen in the wrong location or it may be wrongly conjoined with other features (Treisman & Gelade, 1980, Experiments 8 and 9). Incomplete information from pooled feature activity and from the master map of locations is combined to form object representations that are consistent with the data available but not necessarily accurate. The master map will give some indication of the number of elements or the density of occupied locations present in the display, but it will not indicate which features occupy which locations. If attention is globally spread, the features of global shapes and boundaries will be available. Finally, there will also be evidence in the feature maps specialized for size or spatial frequency of the range of sizes of the elements present.

*Relation to Other Theories of Early Vision*

How does this general account relate to other theories of early vision? The two most detailed proposals within psychology are those of Julesz (1984) and Beck (1982; Beck et al., 1984). Clearly, our account shares many ideas with theirs. All three assume some decomposition of the input into more elementary parts or properties and suggest that the resulting visual primitives are detected automatically and in parallel. It may be more useful to focus on the points where we differ, because these should lead to further research and clarification. Beck's main concern has been with issues separate from ours, namely the mechanisms by which preattentively detected features are grouped into more global configurations. In Julesz's most recent articles (Julesz, 1984; Sagi & Julesz, 1987), an important divergence between our hypotheses has appeared: Julesz suggested that preattentive processing determines *where* feature or "texton" differences are located, but not *what* those differences are. His subjects showed an effect of the number of targets on

the exposure duration needed for asymptotic performance in a task requiring detection of an odd one out (a vertical line among horizontal targets or a horizontal line among vertical targets in a background of diagonal lines), but no effect on a counting (or subitizing) task in which subjects discriminated one from two targets, two from three, or three from four. Moreover, asymptotic performance was reached at the same exposure duration in this counting task and in a task requiring accurate localization of vertical or horizontal target lines among diagonal distractor lines. Our model, on the other hand, has information at the preattentive level about both what (in the feature maps) and where (in the master map of locations); only the relation between the two is as yet unspecified. We showed that subjects could make forced choice discriminations of features at rates substantially better than chance, even when they were incorrectly localized (Treisman & Gelade, 1980). Thus the presence and identities of particular features can be detected without their locations, although once detected they may rapidly call attention by activating the links from the relevant feature map to the master map of locations.

Second, we differ from Julesz on whether certain particular features should be included in the vocabulary of visual primitives. Intersection is a texton for Julesz, but it did not appear to be preattentively detectable in our Experiment 8. Julesz (1984) listed other textons, which for us would be conjunctions of features. For example, "a vertical elongated red blob" is called a texton, but for us it would constitute a conjunction of the features vertical, red, and elongated (or length *x*). The fact that these features can be exchanged to form illusory conjunctions (Treisman & Schmidt, 1982) suggests that their conjunctions cannot be elementary units. Similarly, conjunctions such as these require serial search in a background of stimuli, each of which shares one of their properties. A vertical red bar among vertical blue bars and circular red blobs would be unlikely to pop out, although each would presumably count as a unique texton for Julesz.

A third point on which we may differ is the claim by both Julesz (1984) and Beck (1982) that texton differences are extracted on a local basis over a limited distance. This appears to conflict with our finding that a locally unique item (e.g., a red *H* in a background of green *H*s) can be preattentively masked by the presence of red *X*s elsewhere in the display (Treisman, 1982). We suggest that any local effects that are found may depend on the direct coding of relational features (e.g., contrast or convergence).

Finally, Julesz suggested that the preattentive system can count (subitize) up to four or five items in parallel. In our account, the preattentive system may distinguish different overall levels of activity in the pooled response, but counting would require individuation, localization, and therefore, focused attention. An exception would be if the number of items in a particular type of display were correlated with another preattentively detected feature, such as density of contour or intensity at low spatial frequency (as in Experiment 2 with pairs vs. single lines). Note that although the pooled response of red detectors might be the same to one large red area and to two half-sized red areas, the difference between these displays would be independently coded by size detectors and would also be represented in the master map of filled locations.

Further research should eventually resolve these issues and

give us a clearer understanding of the early coding used by the visual system.

## Links to Physiology

Until recently, there has been little evidence regarding the physiological mechanisms of spatial attention in conditions with multiple stimuli and potential overload. The parietal lobes appear to be involved with expectancy and spatial orienting in the detection of stimuli in an otherwise empty field (Bushnell, Goldberg, & Robinson, 1981; Critchley, 1953; Goldberg & Bruce, 1985; Mountcastle, Anderson, & Motter, 1981; Posner, Cohen, & Rafal, 1982; Wurtz, Goldberg, & Robinson, 1982), and the superior colliculus is implicated in attention when linked with the control of eye movements (Goldberg & Wurtz, 1972). But the problem of selecting stimuli to reduce interference with complex displays or rapid presentation rates has so far been little explored. One exception is the research on evoked potentials in humans (summarized by Hillyard, Munte, & Neville, 1985), which shows that $N_{100}$ potentials are enhanced for attended and reduced for unattended stimuli, but only when attention is overloaded. Hillyard has also shown that visual selection is based initially on single features and only later in time on conjunctions (Hillyard & Munte, 1984; see also Harter & Aine, 1984), findings that are consistent with our speculations from behavioral data. Crick (1984) has suggested that spatial selection in complex displays may depend on alternating bursts of firing and longer phases of inhibition in certain groups of thalamic neurons, and that these bursts of activity may induce temporary synapses among cortical neurons to code transient conjunctions of properties.

Units at later stages of visual processing typically have large receptive fields. Moran and Desimone (1985) pointed to the problem this poses of distinguishing wanted from unwanted stimuli when multiple stimuli are present within one receptive field. If two or more stimuli are present in any given receptive field, their effects will presumably be pooled. We see selective attention as a mechanism not for enhancing selected inputs but for inhibiting inputs from all but a selected item or group (cf. the early versions of filter theory, Broadbent, 1958; Treisman, 1964). A shadow or a mask with an aperture for selected items may be more appropriate analogies than the usual spotlight. Moran and Desimone described experiments which suggest that attention does narrow the spatial extent of extrastriate receptive fields. The same stimulus that produced a large response in a given cell in $V_4$ when attended, produced a greatly attenuated response (about one third of the original) when another stimulus falling within the same receptive field (but not itself capable of activating the cell) was receiving attention. Interestingly, the attenuation of the unattended stimulus occurred only when the attended stimulus fell within the receptive field of the same cell, and not when attention was directed elsewhere. There was no evidence for selective enhancement of attended stimuli. The results suggest that attention works by gating inputs, but it does so only for inputs to cells within which irrelevant information might otherwise be pooled with that from the relevant stimulus. At the level of inferotemporal cortex area (IT), receptive fields are so large that attention affects almost all responses. Thus the outputs from irrelevant units in $V_4$ are presumably

gated at the point at which they converge onto units with even larger receptive fields in IT.

Figure 15 shows a possible arrangement that could give the results described by Moran and Desimone and that may also be consistent with our search results. In Figure 15a attention is narrowly focused on one item and inhibits the effects of other items within the same receptive field. Stimuli in other receptive fields are gated only later, at the point at which their effects would otherwise merge with those of the relevant item. In Figure 15b attention is spread over several items within a receptive field, and in 15c it is spread over a wider area and therefore has effects only at the higher level where receptive fields cover more of the field. We have here a possible instantiation of the feature-pooling mechanism we proposed to account for our search results. The position of the attention mask and the size of the aperture would be selected within the master map of locations, and the required size of the aperture would determine the level at which inhibition would gate further transmission for all the different features that are processed in parallel. Conjunctions would be coded either as shown in the figure, by convergence onto units coding many features, perhaps in area IT, or by the pattern of simultaneous activation among a set of units coding the separate features in the same attention fixation.

The master map of locations could (but need not) be in the parietal lobe. The posterior parietal cortex appears to form part of a pathway involved in representing the spatial lay-out of the visual field (Ungerleider & Mishkin, 1982), and it is also clearly involved in the control of spatial attention (see references cited earlier). Alternatively, the master map could perhaps correspond to area $V_1$ where many units appear to code several properties at once—a particular size or spatial frequency, orientation, color, binocular disparity, luminance, and contrast (Hubel & Wiesel, 1977; Thorell, De Valois, & Albrecht, 1984)—with an orderly topological mapping of retinal locations represented in the arrangement of cell columns. Areas beyond $V_1$ appear to specialize in abstracting particular properties from the multidimensional array. Attention would gate the access to each of these specialized areas to whatever degree of spatial precision is required (or possible, given time constraints) and would do so at the latest stage consistent with preventing unwanted pooling within receptive fields. The fact that each area also projects back to the areas from which it receives input should make this interactive control possible.

The model can account for a recent finding by Houck and Hoffman (1986) that would otherwise be puzzling in the feature-integration framework. They found that contingent adaptation effects (McCollough, 1965) were independent of the direction or load on spatial attention. If adaptation takes place within $V_1$ before different features are abstracted out, it could selectively influence the channels carrying particular combinations of values, whatever the direction of attention. For example, after adaptation to red vertical and green horizontal gratings, black vertical lines would generate more activity in green vertical than in red vertical detectors at the early cortical level, which would therefore pass on to later color-only channels a preponderance of activity signaling green over red.

These suggestions are highly speculative and are intended only to indicate a possible way of integrating our behavioral results with what is known of visual physiology.
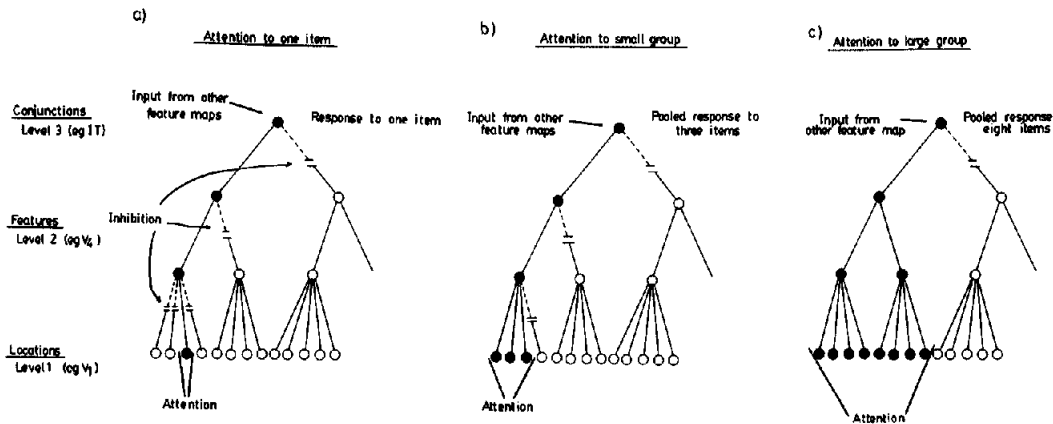
Figure 15. Possible model for pooled responses and attentional control of feature selection.

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## Call for Nominations: *Journal of Experimental Psychology: Learning, Memory, and Cognition*

The Publications and Communications Board has opened nominations for the editorship of the *Journal of Experimental Psychology: Learning, Memory, and Cognition* for the years 1990–1995. Henry L. Roediger III is the incumbent editor. Candidates must be members of APA and should be available to start receiving manuscripts in early 1989 to prepare for issues published in 1990. Please note that the P&C Board encourages more participation by women and ethnic minority men and women in the publication process and would particularly welcome such nominees. To nominate candidates, prepare a statement of one page or less in support of each candidate. Submit nominations no later than April 4, 1988, to

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