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Search Asymmetry: A Diagnostic for Preattentive Processing of Separable Features

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The search rate for a target among distractors may vary dramatically depending on which stimulus plays the role of target and which that of distractors. For example, the time required to find a circle distinguished by an intersecting line is independent of the number of regular circles in the display, whereas the time to find a regular circle among circles with lines increases linearly with the number of distractors. The pattern of performance suggests parallel processing when the target has a unique distinguishing feature and serial self-terminating search when the target is distinguished only by the absence of a feature that is present in all the distractors. The results are consistent with feature-integration theory (Treisman & Gelade, 1980), which predicts that a single feature should be detected by the mere presence of activity in the relevant feature map, whereas tasks that require subjects to locate multiple instances of a feature demand focused attention. Search asymmetries may therefore offer a new diagnostic to identify the primitive features of early vision. Several candidate features are examined in this article: Colors, line ends or terminators, and closure (in the sense of a partly or wholly enclosed area) appear to be functional features; connectedness, *intactness* (absence of an intersecting line), and acute angles do not.

The ease with which we can find a target in a display of distractors depends on their discriminability. This sounds so obvious that no one would wish to question it. Yet search times sometimes differ dramatically between two conditions that involve exactly the same discrimination when the roles of target and of distractors are interchanged. We refer to this pattern of results as a *search asymmetry*. This article describes some search tasks in which a striking asymmetry is present and attempts to assess its theoretical implications.

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Our aim was to use the search task as a diagnostic tool to identify functional features in visual perception. There is widespread agreement, both in psychology and in computational vision, that the early stages of visual processing extract a number of primitive features or properties automatically and in parallel across the visual field (e.g., Beck, 1967, 1982; Julesz, 1975, 1984; Marr, 1982; Treisman & Gelade, 1980). This early coding parses the scene into separate regions by differences in simple features such as brightness, orientation, or color, and thus establishes candidate objects for later identification. There is less agreement on exactly which properties of the visual image function as the primitives of early vision. The dimensions used by physicists to describe the external world do not necessarily correspond to those which are coded by the visual system. Living organisms have presumably evolved the sensitivities which are useful to them in interacting with the world to procure food, rest, safety from predators, and so on (Gibson, 1966). These may be specialized to detect complex combinations of simple physical dimensions like wavelength, intensity, size, and distance.

A number of diagnostics have been proposed to identify the elementary features that function as words in the language of visual processing (see review by Treisman, in press). These features would, by definition, be separately coded; any pair of physical properties that are not separated in perceptual analysis would count as one unitary or integral perceptual feature (Garner, 1974).

Evidence for the existence of separable features includes physiological recordings from single units, showing different trigger properties for individual cells in different visual areas of the brain (see for example, Cowey, 1979; Hubel & Wiesel, 1968; Zeki, 1981); selective adaptation with different visual stimuli to reveal specialized aftereffects (e.g., the waterfall illusion) or selective changes in threshold for stimuli which share particular properties with the adapting stimulus although differing in other properties (see for example, the review by Anstis, 1975); investigations of texture segregation to determine the properties that are processed automatically and in parallel, and that parse the visual scene into potential figures and ground (see for example, Beck, 1967, 1982; Julesz, 1981); the analysis of visual confusions and of similarity judgments to infer the dimensions along which errors are made or by which judgments of similarity are independently determined (see for example, Gibson, 1969; Tversky, 1977); selective attention tasks, such as speeded classification, which identify properties that can be processed selectively without interference or facilitation from variation in other properties (Garner, 1970); and finally, the occurrence of illusory interchanges in which features from one object are wrongly conjoined with features from another simultaneously presented object (Treisman & Schmidt, 1982).

So far, a somewhat heterogeneous collection of features has emerged from the various diagnostic tests as possible elementary perceptual units; they range from relatively uncontroversial candidates, like particular colors or line orientations, to more subtle and abstract properties, like symmetry, closure, or even the patterns of X-rays that signal to a trained physician the presence of a tumor. It seems important for psychologists to test the same candidate features by several different criteria. Garner (1970, 1974) proposed three such converging operations to identify separable properties (a city block metric inferred from similarity judgments, independent effects of each property on speeded classification latencies, and independence in absolute judgment tasks), and offered evidence supporting separability for such properties as color, shape, size, but not for hue, value, and chroma. Treisman and Paterson (1984) showed correlations, both across subjects and for particular stimuli, between three other criteria (parallel detection in search, easy texture segregation, and illusory conjunctions).

Even when the different tests appear to agree, it is sometimes difficult to identify precisely the property that mediates performance. It may, for example, be important to distinguish properties (such as vertical, or moving left) from parts or components of shapes (such as lines and angles) which themselves have properties. Suppose that areas containing *T*'s segregate well from areas containing *O*s, *C*s, and *S*s. We infer that the *T* has a preattentively coded feature which mediates segregation, but we cannot pin down which of many possible differences are determining performance. Are the critical features the parts of the letters (such as their lines or angles), or some properties of those parts (such as their orientation or their straightness), or some emergent or wholistic property (such as top-heaviness), or even the complete letters themselves as unitary configurations? Is segregation in fact mediated by just one feature at a time or may several play a part? Is the same complete set of features automatically extracted when *T*s are presented next to *O*s and *C*s and when they are presented next to *V*s and *X*s, or is a different subset of features coded to define the differences between the figure and its current background? In other words, are features inherently flexible and relational, or is there a fixed, limited vocabulary of features available at the early stages of visual processing? We could even question the assumption that individual items in the display are the carriers of features. The visual system might directly code relations or discontinuities between adjacent items, such as the relation "darker than" or "sparser than."

Beck (1982) proposed that texture segregation emerges from the activity of difference detectors at boundaries.

We are far from having definitive answers to these questions, but in this article, we propose a possible new source of evidence which may contribute to clarifying the functional language used in early vision. We use a particular pattern of latencies in visual search—the so-called *pop-out* effect—as a further diagnostic for simple features, and we examine the conditions under which it occurs. When a target in a visual search task is detected with little change in latency as the number of distractor items is varied, we infer that its critical property (or properties) is processed spatially in parallel. Because detection occurs without focused attention, we assume that it is mediated by a relatively early stage of visual processing. As Neisser (1963) put it, the subject sees only a blur until the target "jumps out at him." The consistent pattern, which defines pop-out as we use it in this article, is a flat or almost flat function (less than 5- or 6-ms per item) relating detection latency to the number of distractor items on trials when the target is present. When the target is absent from the display, the function may also be flat if subjects are confident that the target would pop out if present, but may increase (usually not linearly) if subjects check to make certain that they are not missing the target.

We contrast parallel search and pop-out with the pattern of latencies characterizing serial processing. The main diagnostic for serial search is a linear increase in search latency as distractors are added to the display. When the slope on negative (target absent) trials is twice as steep as the slope on positive (target present) trials, we infer that the serial search is also self-terminating (Sternberg, 1966). In other words, subjects respond on positive trials as soon as they find the target, but check the complete display before deciding that it is absent. These inferences from search times have been questioned (e.g., Townsend, 1972), and it is certainly true that some parallel models can mimic the linear increasing functions generated by serial processing. Flat functions and pop-out are hard to reconcile with any but a parallel model. However, in choosing to interpret linear increasing functions with a 2:1 slope ratio as evidence for serial self-terminating search, we rely on additional evidence, such as the relation between the variances of search latencies and display size, and the dependence of correct identification on accurate localization for targets that appear to be detected serially (Treisman & Gelade, 1980).

In previous work, we showed that targets defined by a single physical feature which is very likely also to be perceptually separable (e.g., a particular color or a curved shape among straight ones) *pop out* of a display of distractors, regardless of how many are present, whereas targets defined only by a conjunction of features require serial search (Treisman & Gelade, 1980). Prolonged practice with particular arbitrary sets of target letters and distractor letters has also been shown to lead to parallel detection in search for stimuli that initially require serial processing (Schneider & Shiffrin, 1977). A necessary condition is that the target and the distractor sets are never interchanged and a constant mapping of stimuli to responses is preserved. We might infer that extended and consistent perceptual learning leads to the formation of new feature detectors responding to the targets as unitized wholes rather than as conjunctions of features (Laberge, 1973). In the present article, however, we report only studies with relatively unpracticed search tasks.

When search is serial, we infer that it requires focused attention. In fact we equate attention in this context with the serial scanning device, as if a mental spotlight were directed to each item in turn in order to allow its accurate identification. We have used converging operations to confirm that attention is required when features must be located and conjoined; thus we found that the identification of items that require serial search is also (a) facilitated by advance cues allowing prior focusing of attention on their spatial location and (b) impaired in predictable ways when attention is diverted to another visual location or divided over many locations (Treisman, 1979; Treisman & Gelade, 1980; Treisman & Schmidt, 1982; Treisman, Sykes, & Gelade, 1977).

We took as a starting point a further prediction from feature-integration theory (Treisman & Gelade, 1980; Treisman, Sykes, & Gelade, 1977). The theory suggests that separable features are registered in parallel across the visual field, but that they are initially in some sense "free-floating." If serial attention is needed to conjoin features, it should also be needed to localize the absence of a feature from a particular item, whenever the same feature is present in other items. Thus a target characterized by a unique feature should be detectable by the mere presence of activity in the relevant feature detectors, without any need to localize each distractor. On the other hand, if the feature is present in all items except the target, each will have to be checked in turn in order to localize the one item which is not conjoined with the relevant feature. Experiment 1 tested the presence of the predicted asymmetry in search latencies with stimuli to which a single feature could uncontroversially be added.

If the asymmetry materialized between search for a target with the feature present and search for a target with the feature absent, we hoped to use it as a new tool to diagnose more controversial perceptual features. It should also allow us to distinguish between features that we can label *substitutive*, for which the absence of a feature in a given stimulus implies the presence of another, and features that can be removed without being replaced by others (Garner, 1978). The former features usually constitute a set of values on a dimension like color, where, if the dimension can be applied to a stimulus at all, one value cannot be removed without being replaced by another. If a visual area loses its redness, it must gain some other color (including white or grey as possible colors). Features which can be removed without replacement are often parts or components, but they need not be. For example, closure and symmetry can be present or absent for a particular stimulus, although they are not parts of it. If they are absent, they are replaced by their negations, openness, and asymmetry. In this case, it is an empirical question whether the negations are also preattentively coded features or not.

Experiment 1: Asymmetry in Search for Feature Presence and Absence

The first experiment was designed to test the presence of the predicted asymmetry between two search tasks which differed only in the allocation of stimuli to the roles of target and of distractors. More specifically, when the target clearly possesses a feature or component which the distractors do not, is it easier to find than when the target clearly lacks the same feature or component which the distractors possess? We chose a pair of items that were identical to each other except that one had an extra component that the other lacked: a circle either with or without a vertical line which intersected the base (see Figure 1). In one condition (*presence*), the target had the line and the distractors did not, so subjects could look for the presence of the line; in the other condition (*absence*), each distractor had the line but the target did not, so subjects were to look for the absence of the line.

Method

Stimuli. The experiment was run with a two-field Cambridge tachistoscope with exposure durations controlled by an IBM personal computer, which also recorded the subjects' key-press reaction times. Cards were made with black ink pens and stencils; the background luminance on the white cards was about 4.0 ml. The displays consisted of circles with or without an intersecting vertical line. These shapes were haphazardly scattered within an area subtending 8.8° × 11.4°. The circles had diameters of 1.4°; the intersecting lines were 1.0° long and cut vertically through the lowest point on the circumference of the circles, extending 0.5° above and below the intersection. Two decks of 72 cards each were made: In one deck (presence), the distractors were circles without lines, and the target, when present, was a circle with an intersecting line. In the other deck (absence), all the distractors had intersecting lines, and the target, when present, did not. Half the cards included a target, and the other half did not. Three different display sizes were used in each case: 1, 6 and 12 items. The target, when present, appeared equally often in each quadrant for each condition and each display size, and equally often in the inner ⅓, middle ⅓, and outer ⅓ of the display area. Twelve different cards were made for each display size with target present, and 12 with target absent. Figure 1 shows examples.

Subjects. Eight subjects (4 men and 4 women) were run in this experiment. They were all students at the University of British Columbia (UBC), who volunteered and were paid $4 an hour.

Procedure. Each subject was run in both the presence and the absence conditions. The order was counterbalanced across subjects, and 15 practice trials were given before each condition (more if subjects made errors or were very slow). Each condition comprised three blocks of 72 trials each (12 examples for each of 3 display sizes for both positive and negative displays). A central fixation dot was present between trials. A 1000-Hz warning tone was sounded for 300 ms before each display, and the display remained present until the subject responded. Subjects were asked to press one key, if the target was present in the display, and the other key, if it was not, and to do so as quickly as they could while minimizing errors. Half the subjects pressed with their right index finger for target present and their left index finger for target absent, and half the subjects did the reverse. If they made an error, they heard a low-pitched noise lasting 1,100 ms; the trial was rerun later in the block.

Results and Discussion

The mean search times are shown in Figure 2. The best-fitting lines were calculated and

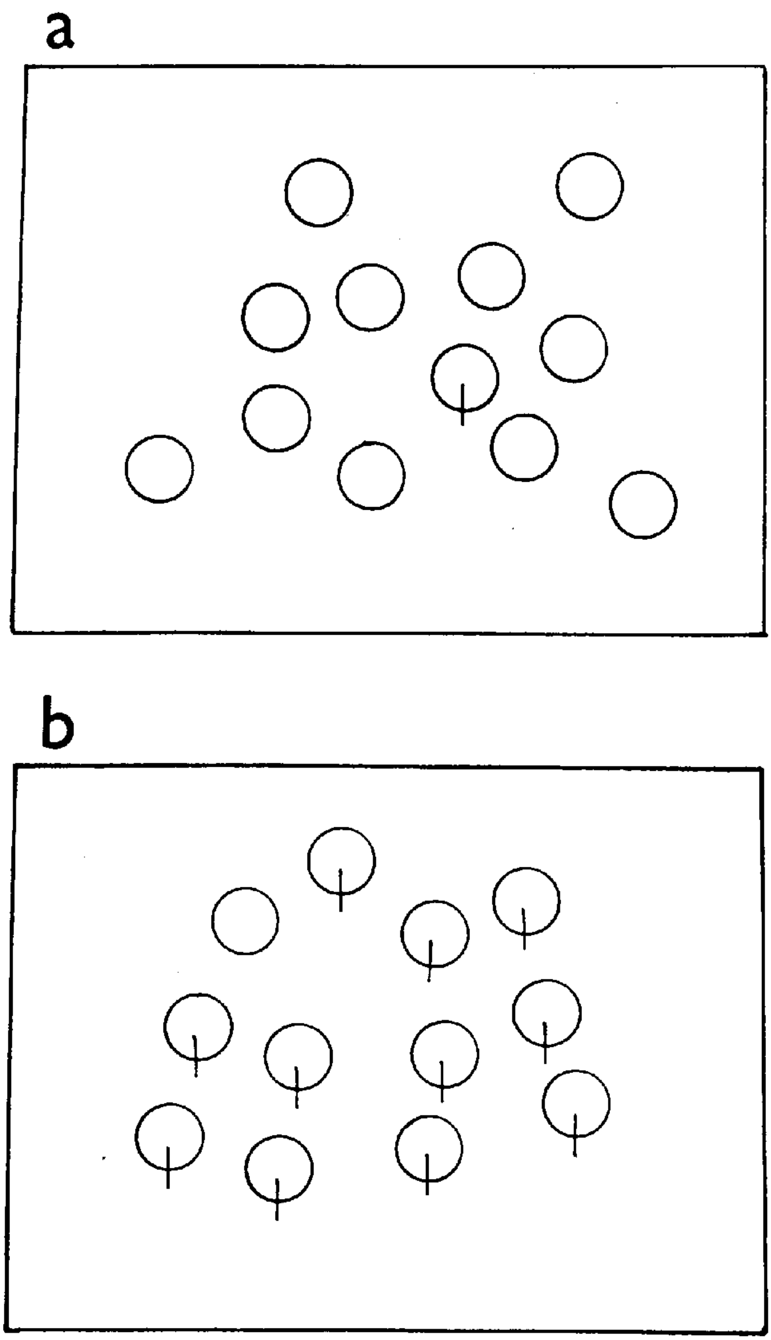

Figure 1. Examples of displays of 12 items with target present for each type of target.

the slopes were as follows: for the target with the line (*feature present*), positive responses gave a slope of 4.0-ms per item; negatives gave a slope of 2.9 ms. The effect of display size (number of items) was significant, $F(2, 14) = 17.23$, $p < .001$, but small. On the other hand, for the target without a line (*feature absent*), positives gave a slope of 19.7 ms per item and negatives a slope of 38.9 ms per item. The effect of display size was again significant, $F(2, 14) = 66.47$, $p < .001$, and much larger than with the line present targets. The functions for line absent were almost perfectly linear, with linearity accounting for 99.5% of the variance due to display size for positives and 99.8% for negatives (compared with 88.4% and 96.4% for line present targets). An analysis of variance (ANOVA) on the pooled results showed significant effects of target, $F(1, 7) = 89.9$, $p < .001$, of display size, $F(2, 14) = 72.2$, $p < .001$, and of positive versus negative displays, $F(1, 7) = 20.35$, $p = .003$. The interaction between target type and display size was highly significant, $F(2, 14) = 53.94$, $p < .001$, as were the interactions of target type with positive versus negative displays, $F(1, 7) = 45.70$, $p < .001$, and the three-way interaction between target type, display size, and positive versus negative displays, $F(2, 14) = 17.08$, $p < .001$.

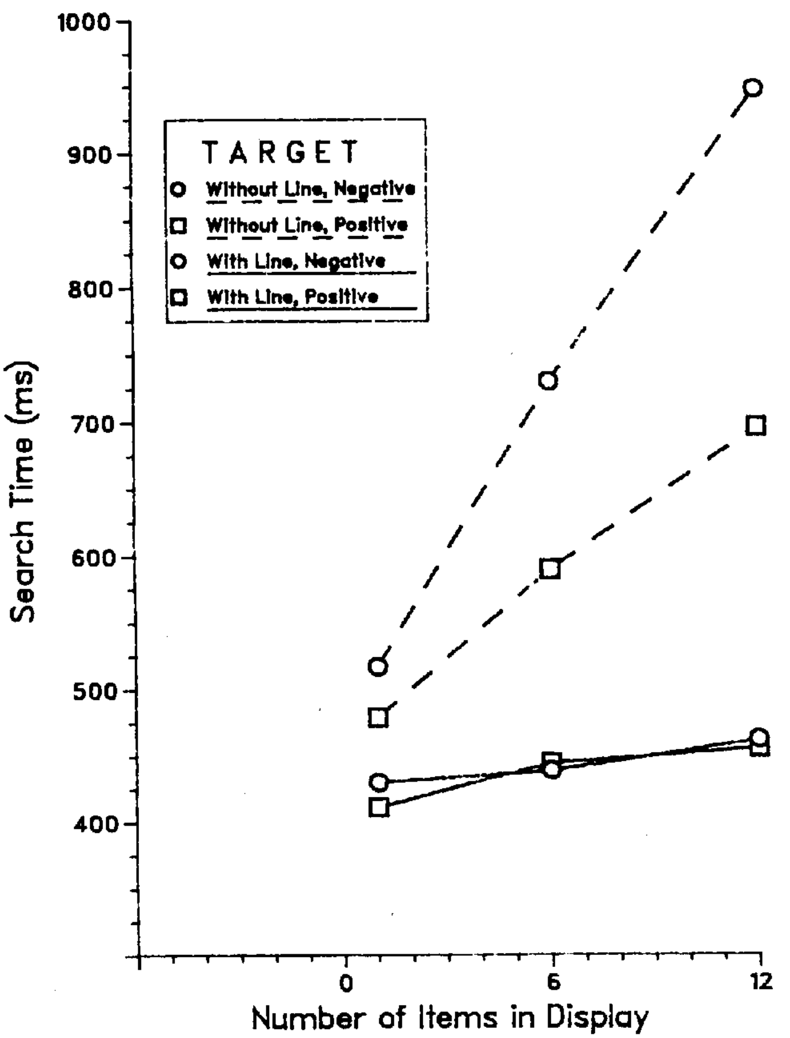

Figure 2. Search times in the different conditions of Experiment 1.

All error rates were below 4% except for the positive displays of 12 containing the target without a line, where they averaged 13.9%. Subjects therefore missed seeing a considerable number of circles without lines when these were embedded in displays of 11 circles with lines.

The same subjects were run with both target–distractor allocations. The reversal of stimulus–response mapping might be expected to produce considerable interference (Schneider & Shiffrin, 1977). However, it seems that with simple displays and targets that differ from the distractors in one feature only, varied mapping does not force serial search. Slopes were almost flat for the line target, whether it was run first (mean 2.6 ms per item) or second (mean 4.5 ms per item). For the target without a line, the difference was in the opposite direction and was also not significant (33.5 and 25.2 ms per item, for subjects who experienced that condition first and second, respectively). There is therefore no evidence of negative transfer from the reversal of mapping in the conditions we used; the differences are in opposite directions and largely reflect the slow performance of the same single subject in the two conditions.

The most striking finding is the asymmetry between search for the presence and search for the absence of the line intersecting a circle. Although the presence of one intersecting line is detected very fast and with little effect of display size (only 3- or 4-ms per distractor), the target circle without an intersecting line was detected only through a slow and apparently serial search, requiring 40 ms to check each distractor. For feature absent, the functions were completely linear and the ratio of positive to negative slopes approximated 1/2, suggesting that search was self-terminating. The same discrimination between a shape with and a shape without an added line apparently poses a different perceptual problem when embedded in these two versions of the search task.

We infer from the results that the circle with an intersecting line possesses one or more features which are absent from an intact circle. The results do not specify what those features are; possible candidates are straightness, vertical orientation, intersection, angles, and line ends (terminators). Further experiments would be needed to determine which are critical. For the present, our aim was to demonstrate a search asymmetry between targets which differed from the distractors in possessing or in lacking one or more preattentively detected features.

The results are consistent with the prediction from feature-integration theory, that the presence of a primitive feature can be detected without its location being available. In search for the presence of the line, there is no need to determine which circle it intersects. The presence of an intersecting line anywhere in the display should be sufficient to trigger a positive response. Once detected, it is likely to attract attention if the display remains available, but localization may follow rather than precede detection. Search for the absence of a feature is another matter. In displays with many intersecting lines, the task requires that subjects find a circle that does not have a line; in other words, they must check each circle to determine whether or not it is conjoined with a line. If features are free floating at the preattentive level, the different features of the distractor lines and circles should be detected, but not related spatially unless and until attention can be focused serially on each in turn.

Neisser (1963) first reported an asymmetry in search many years ago. When subjects searched for a line of letters which did *not* contain a *Q* (in a list of lines which did contain a *Q*), they took much longer than when they searched for a line which *did* contain a *Q* (in a list of lines which did not). Although Neisser's results also demonstrate an asymmetry in search for the presence and for the absence of a particular target, his task posed very different perceptual demands from those that interest us. The target in search for presence was clearly specified, whereas the distractors were heterogeneous (any other letter); on the other hand, the target in search for absence could take a large variety of forms (any combination of letters other than *Q*). The only possible strategy in search for absence was to check each line for the presence of a *Q* until that test failed. In the present experiment, both the distractors and the target were uniquely specified in both conditions; they simply exchanged their roles.

Another intriguing asymmetry of search

was reported by Frith (1974) and by Richards and Reicher (1978). Both studies showed that unfamiliar items (mirror imaged, inverted or mutilated letters, or Gibson shapes) were detected more rapidly in displays of familiar items than the same familiar items were in the same unfamiliar distractors. Could this be an example that fits our framework? If so, it would suggest that novelty or unfamiliarity is a primitive perceptual feature, whereas familiarity is not. However, neither familiar nor unfamiliar targets mediated pop-out in the sense in which we use it here. Search rates averaged 20 to 25 ms per item for positives and 50 to 60 ms per item for negatives, in Richards and Reicher's "faster" condition (familiar distractors). This suggests that the items were treated as conjunctions of features in both cases. Alphanumeric characters in fact share many components in different combinations. If search is serial in both cases, the difference should reflect the speed with which the distractors can be serially checked to determine whether they meet the target specification. Familiar letters are identified faster than unfamiliar ones, giving rise to the observed asymmetry. This account is close to the one proposed by Reicher et al. and sounds quite plausible for these stimuli. The present experiment on the other hand, showed flat functions, implying parallel search, in one version of the two target–distractor assignments.

Experiment 2: Search for Presence and Absence of Line and of Color Features; Effects of Distractor Heterogeneity

The second experiment had two main aims. First we replicated the line search task comparing homogeneous and heterogeneous shapes, to see whether the flat pop-out function for the presence of the line target depended on the distractors all being identical circles. Several earlier studies have shown a large distractor heterogeneity effect in search and suggested that identical stimuli may be processed in a special way (e.g. Eriksen, 1953; Gordon, 1968; McIntyre, Fox, & Neale, 1970; McLaughlin, Masterson, & Herrmann, 1972). Some have proposed that distractors are processed faster when they are identical (McLaughlin, Masterson, & Herrmann, 1972), or that identical distractors can be compared to the target in parallel, whereas heterogeneous ones require serial comparisons (McIntyre, Fox, & Neale, 1970). The probability of confusion between one or more distractors and the target also increases with the number of distractors which share different properties with the target (Estes, 1974). All these accounts assume that the distractors are processed or identified as a necessary part of target detection. We suggest, instead, that in cases where the target possesses a unique feature which the distractors lack, search may require only a parallel check of all locations for the presence of the target feature. In this case, irrelevant variations in the distractors should have no effect when the target pops out. On the other hand, if heterogeneity slows the serial checking of distractors, it could have a substantial effect when the target does not pop out. In order to see if distractor heterogeneity interacts with search for feature presence or absence, we used displays consisting of randomly mixed circles and isosceles triangles, again with or without vertical lines intersecting the base.

Second, we compared search for presence and for absence with another simple feature, the color green. The color green differs from the line feature in a critical respect: it is a substitutive feature in that its absence implies the presence of another color, which may be equally salient and preattentively detectable. Although the instructions were logically the same in the line and the color tasks, the problem they pose for the perceptual system might be quite different. In this version of the experiment, subjects were told either to look for the presence of a green target among red and black distractors, or to look for a target that was not green (and was therefore red or black) among distractors that were all green. Because red and black are presumably features with equal status to green, we did not expect an asymmetry at the feature level; if one were found, it could be attributed either to the effect of the negative absence instructions, or to the fact that the target, once recoded as the presence of red or black, was defined disjunctively instead of uniquely (green).

Method

Stimuli. The equipment was the same as that in Experiment 1, except that vocal reaction times were collected instead of key presses, using a Gerbrands voice-operated relay. There were two kinds of display: shapes with intersecting lines and colored shapes. The stimuli were scattered haphazardly over an area subtending 8.8° × 10.1°, except that target locations were counterbalanced across quadrants and inner and outer areas, as in Experiment 1.

The shapes with lines were circles, as in Experiment 1, or isosceles triangles 1.5° high × 1.6° base. Two decks of 48 cards were made, comprising eight examples for each of three display sizes (4, 8, 12) and target present or target absent. In one deck (feature presence), the distractors were shapes without lines and the target, when present, was a shape with an intersecting line. In the other deck (feature absence), all the distractors had intersecting lines and the target, when present, did not.

The color stimuli were red, green, or black *O*s (1.1° in diameter) and *X*s (1.0° tall × 1.0° wide). Again, two decks of 48 cards each were made: In one deck (presence), all the distractors were red or black (randomly mixed in equal numbers), and the target, when present, was green. In the other deck (absence), the distractors were all green, and the target, when present, was not green (equally often red or black).

Half the displays in each condition contained a target, and half did not. Three display sizes, 4, 8, and 12 items, were randomly mixed in each condition. As before, the positions of the targets were controlled to equate the numbers in each quadrant and in the inner and outer areas of the displays.

A set of 48 homogeneous displays was also prepared for each type of stimulus. For the shape with line stimuli, half the displays contained only circles, and half only triangles. For the color displays, half contained only *X*s, and half only *O*s.

Subjects. Nine subjects (3 men and 6 women) were run in the presence condition, and 9 subjects (4 men and 5 women) were run in the absence condition, with the heterogeneous displays. Six of these subjects in each group were also run on the homogeneous displays to allow within-subject comparisons of the effects of heterogeneity. All the subjects were students at UBC, who volunteered and were paid $4 an hour.

Procedure. This experiment was run together with Experiment 3, with the order of the three sets of stimuli counterbalanced across subjects. We report Experiment 3 separately to simplify the description and discussion.

Each subject was run either in the presence or in the absence condition. The 6 subjects in each group who were run on both the homogeneous and the heterogeneous displays received each possible order of stimulus types (lines, colors, and the triangles of Experiment 3), starting either with the three heterogeneous conditions or with the three homogeneous conditions, giving a complete counterbalancing. The different distractor types in the homogeneous conditions were run in two separate blocks, so that subjects knew for each display what the distractors would be; the order was counterbalanced for these as well. The 3 subjects in each group who ran only on the heterogeneous displays, also had the order of stimulus types counterbalanced. Each block consisted of 3 runs through the deck of 48 cards for the heterogeneous blocks, or 3 runs through the 24 cards of each of the two subtypes for the homogeneous blocks. Trials with different display sizes and with target present or absent were randomly mixed within blocks. Any trials on which an error was made were rerun later in the block. The entire experiment took two sessions for each subject who did the homogeneous and heterogeneous conditions, and one for those who did only the heterogeneous condition.

A fixation dot was present between trials. The experimenter gave a verbal pretrial warning, then triggered the display which remained present until the subject responded. Subjects were asked to say *yes* if a target was present and *no* if it was not. They were asked to respond as quickly as possible while minimizing errors. At least 12 practice trials were given before each new type of stimulus was tested.

Results and Discussion

The calculated best-fitting slopes and intercepts for the functions relating search times to display size are given for each condition in Table 1; the results reflect the means for the 6 subjects who were run in both the homogeneous and the heterogeneous conditions. The mean search times for all 9 subjects who ran in the heterogeneous condition are shown in Figure 3. Error rates were all below 6% except, again, for the shape without a line in the largest display size, where subjects missed on average 10% of targets.

We look first at the pattern of performance with the line and with the color, using the data from the 9 subjects in the heterogeneous condition. The results with the line stimuli are similar to those of Experiment 1. Again a striking asymmetry appears between the search latencies for the line target and for the absence-of-line target. The difference between search for the shape with the intersecting line and search for the shape without it was highly significant, $F(1, 16) = 60.17$, $p < 0.001$; this factor interacted both with display size, $F(2, 32) = 57.84$, $p < 0.001$, and with positive versus negative displays, $F(1, 16) = 63.73$, $p < 0.001$; the three-way interaction was also significant, $F(1, 16) = 16.92$, $p < 0.001$. The new finding here is that heterogeneity has a different effect on search for feature presence and search for feature absence. ANOVAs on the 12 subjects who were tested on both the homogeneous and the heterogeneous displays showed no effect on search for the presence of a line; the latencies were in fact slightly shorter for the mixed triangle and circle displays than for homogeneous displays of circles only or triangles only. Thus feature pop-out, when it occurs, does not depend on all the distractors being identical. Nor, however, does homogeneity of the distractors induce parallel search in the feature–absent displays, when no primitive feature is available to uniquely characterize the target.

In search for a shape which lacked an intersecting line, heterogeneity of the carrier shapes significantly slowed performance, $F(1, 5) = 40.59$, $p < 0.001$. Heterogeneity also interacted with positive versus negative displays, $F(1, 5) = 12.47$, $p = 0.017$, and with display size, $F(2, 10) = 15.35$, $p < 0.001$. Heterogeneity seems primarily to have made subjects more cautious in deciding that each shape did have an intersecting line and was therefore not the target. When search is serial, the distractors are presumably identified with focused attention; all their properties are then available and conjoined, and heterogeneity slows the processing of each item in turn. The fact that heterogeneity does interfere with serial search makes the complete absence of interference with targets that pop out all the more informative. It refutes the idea that pop-out results when all the distractors can be identified in parallel because all are identical. Instead, it is consistent with the idea that the distractors receive little or no processing when the target has a preattentively detected feature. The relevant feature is the one that is unique, that pops out of the display when it characterizes the target. A model which would make this possible is one in which different features are registered in separate maps by different perceptual analyzers or modules. If the target is characterized by a feature which is absent from the distractors, its presence can be detected by simply looking for the presence of any activity in the relevant map.

The color conditions differ strikingly from the line conditions: no asymmetry is present here. Both the green target and the nongreen target seem to be detected fast and with minimal effects of the number of distractors (1.5 ms on average) and no effect of irrelevant variations in shape. There was a small but nonsignificant difference in intercept between the green and the nongreen targets: latencies with green targets were 28 ms faster than with nongreen targets, but there was no interaction of target type, with display size, or with positive versus negative displays, and thus no indication of a change from parallel processing of the display with the green target to serial processing with the nongreen target in green distractors. The suggestion is that the absence of green is, in this experiment, recoded as the presence of red or black, and that each of these colors functions equally as a primitive feature. One of two disjunctive targets may be detected slightly more slowly

Table 1
Functions Relating Search Times to Display Size (4, 8, 12 Items) in Each Condition of Experiment 2

Condition	Slope	Slope ratio	Intercept	% Variance due to linearity
Presence: Homogeneous				
Shape and line				
Positive	1.5	2.33	503	69
Negative	3.5		480	100
Color				
Positive	0.1	20.0	488	2
Negative	2.0		454	66
Presence: Heterogeneous				
Shape and line				
Positive	1.8	0.89	510	80
Negative	1.6		481	53
Color				
Positive	2.5	0.96	470	82
Negative	2.4		469	60
Absence: Homogeneous				
Shape and line				
Positive	18.3	1.86	559	98
Negative	34.0		598	100
Color				
Positive	3.0	0.47	529	98
Negative	1.4		526	30
Absence: Heterogeneous				
Shape and line				
Positive	22.6	2.56	616	97
Negative	57.8		586	99
Color				
Positive	1.0	—*	536	37
Negative	−1.8		548	97

Note. In search for presence, the target was a shape with an added intersecting line or a green shape. In search for absence, the target was a shape without an intersecting line or a nongreen shape. The data are those from the two groups of 6 subjects who were run in both the homogeneous and the heterogeneous conditions. *No meaningful slope ratio can be given here because of the negative slope. Essentially both functions are flat against display size.

than a single unique target, but search remains spatially parallel when each of the two potential targets is characterized by a simple feature. Search for any of *n* targets may require *n* successive checks of the display, but each of these can reject all the distractors in parallel, at least when the distractors are uniform in color.

The implication, when one puts the color results together with those from the shape and line conditions, is that no recoding of "shape without line" is spontaneously available which will transform it into the presence of a primitive feature (e.g., intactness) comparable with the recoding of nongreen as red or black.

Experiment 3: Search for the Presence or Absence of Triangle Targets

The line and the color conditions were intended to illustrate two extremes, to be used as standards of comparison in less clear-cut cases. The next experiment tested a more hypothetical pair of features—*closure* and *free ends* (or *terminators*)—in the same paradigm. Treisman and Paterson (1984) reported converging evidence suggesting that closure may function as a visual primitive. Those experiments tested two candidate features ("closure" and "arrow junctions") which may emerge when lines and angles are conjoined in particular configurations. The results established a different pattern of performance for triangles and for arrows made out of the same component right angle and diagonal line, except that the diagonal line was oriented in the opposite direction in the two stimuli (either joining the two ends of the angle to form a triangle, or bisecting the right angle to form an arrow). Triangles were detected in parallel among line and angle distractors; they appeared to mediate easy texture segregation when they were present in one area and angles and lines when they were in another area; finally subjects rarely saw illu-

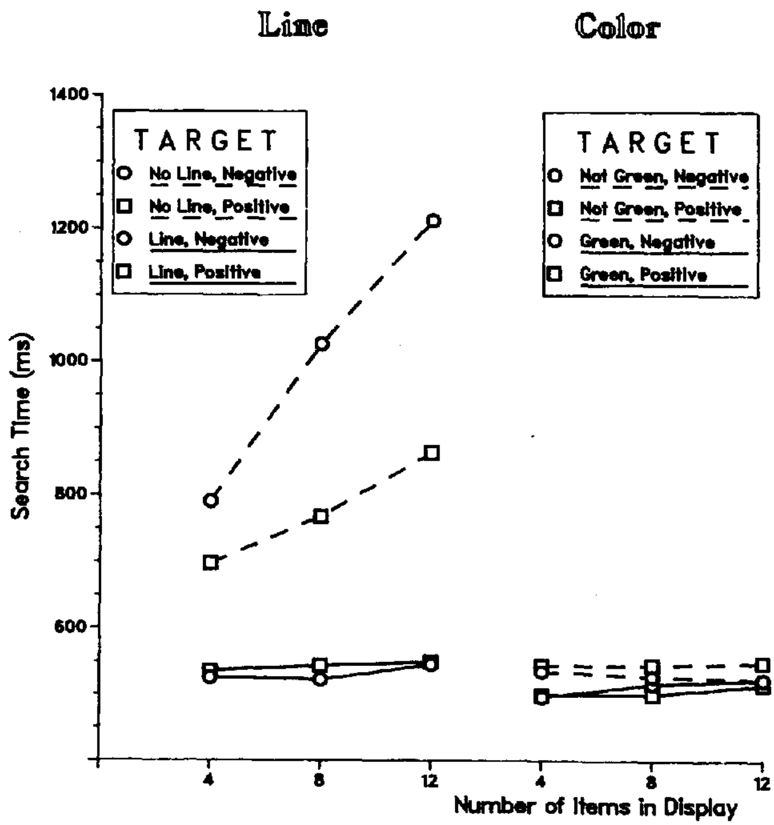

Figure 3. Search times in the different conditions of Experiment 2.

sory triangles when their attention was divided over a briefly presented array of angles and lines. In each case the opposite result appeared to hold with the arrow stimuli, at least for a substantial proportion of subjects. We hypothesized that the difference was due to an *emergent feature* of triangles (cf. Pomerantz, Sager, & Stoever, 1977), perhaps closure, which can be detected automatically and preattentively, whereas for many subjects an arrow has no such emergent features. The arrow therefore must be detected as a conjunction of lines and angles and this, according to feature-integration theory, requires focused attention (Treisman & Gelade, 1980; Treisman & Schmidt, 1982).

Julesz (1981) had earlier reported an apparently conflicting result: He found no texture segregation between areas containing an elongated rectangular *S* (without a closed area) and the same lines configured differently to form a closed rectangle and a horizontal straight line. He concluded that closure is not a preattentively detectable feature; the two figures share the same number of line ends or terminators and therefore are treated as identical in early visual processing. To account for our results, Julesz (personal communication) suggested a different hypothesis: Rather than triangles possessing an additional emergent feature (closure) that is not present in their angles and lines, triangles might lack a feature that is present in their angles and lines, namely *terminators* or *free-line ends*. Terminators are visual features or "textons" (Julesz, 1984), whereas closure is not. Triangles differ sharply from their component angles and lines in the number of terminators they possess (zero versus two), whereas arrows differ less sharply (with three versus two terminators). This might explain the differences we found between the two figures (Treisman & Paterson, 1984). Essentially, the hypotheses differ in that we postulated the presence of a separable feature in triangles, whereas Julesz postulated the absence of a different separable feature. Our assumption was that pop-out in search is mediated by the presence but not by the absence of a primitive perceptual feature. Beck (1973) showed that textural segmentation is stronger for a small number of triangles scattered among angles (triangles with the base missing) than for the same angles scattered among complete triangles. It is possible that this asymmetry in discriminability reflects the greater salience of feature presence than of feature absence, with closure triggering feature detection and the absence of closure detected only by default. However, this assumption clearly needs testing.

We compared search for a triangle among angles and lines with search for an angle among triangles. The angles and diagonal lines were identical to those which formed the triangle (see Figure 4). The question was whether the pattern of performance would closely resemble the shape and line condition or the color condition. If closure functions as a perceptual feature which characterizes triangles but not their component angles and lines, the task with the triangle target could become a search for the presence of the closure feature (analogous to search for the presence of an extra line intersecting a shape). Conversely, search for an angle in triangles could either be mediated by search for the absence of closure (analogous to search for the single shape with no intersecting line), or, if terminators also function as preattentive features, by search for the presence of terminators. In the latter case, there might be no asymmetry; the pattern of performance should resemble that obtained with the colors.

Method

Stimuli. The triangle, angle, and line stimuli consisted of right-angled triangles facing left or right, with the two right-angled sides 0.95° long, right angles the same size as those in the triangles, and separate diagonal lines in the same orientation and the same length as the hypotenuse of the triangles (1.34°). Two decks were made as before: In one deck, the distractors were angles and diagonal lines, and the target, when present, was a triangle. In the other deck, the distractors were triangles, and the target, when present, was an angle. Figure 4 shows examples of the displays. In the homogeneous condition, half the displays contained triangles or angles facing left, and the other half contained triangles or angles facing right. The display sizes and general layout were the same as those in Experiment 2.

Procedure. The experiment was run together with Experiment 2 on the same subjects and following the same procedure. The order of line, color, and triangle decks was counterbalanced across different subjects. Subjects were instructed to search for a complete triangle in one condition and for a "shape which is not a triangle—a right angle" in the other.

Results and Discussion

The mean search times in each condition are shown in Figure 5. When the target was a triangle in angle and line distractors, the result was clear-cut. The triangle was detected almost as fast as the shape with line, and again with little effect of display size. The mean slopes for the 9 subjects in the heterogeneous condition were only 3.0 ms per item

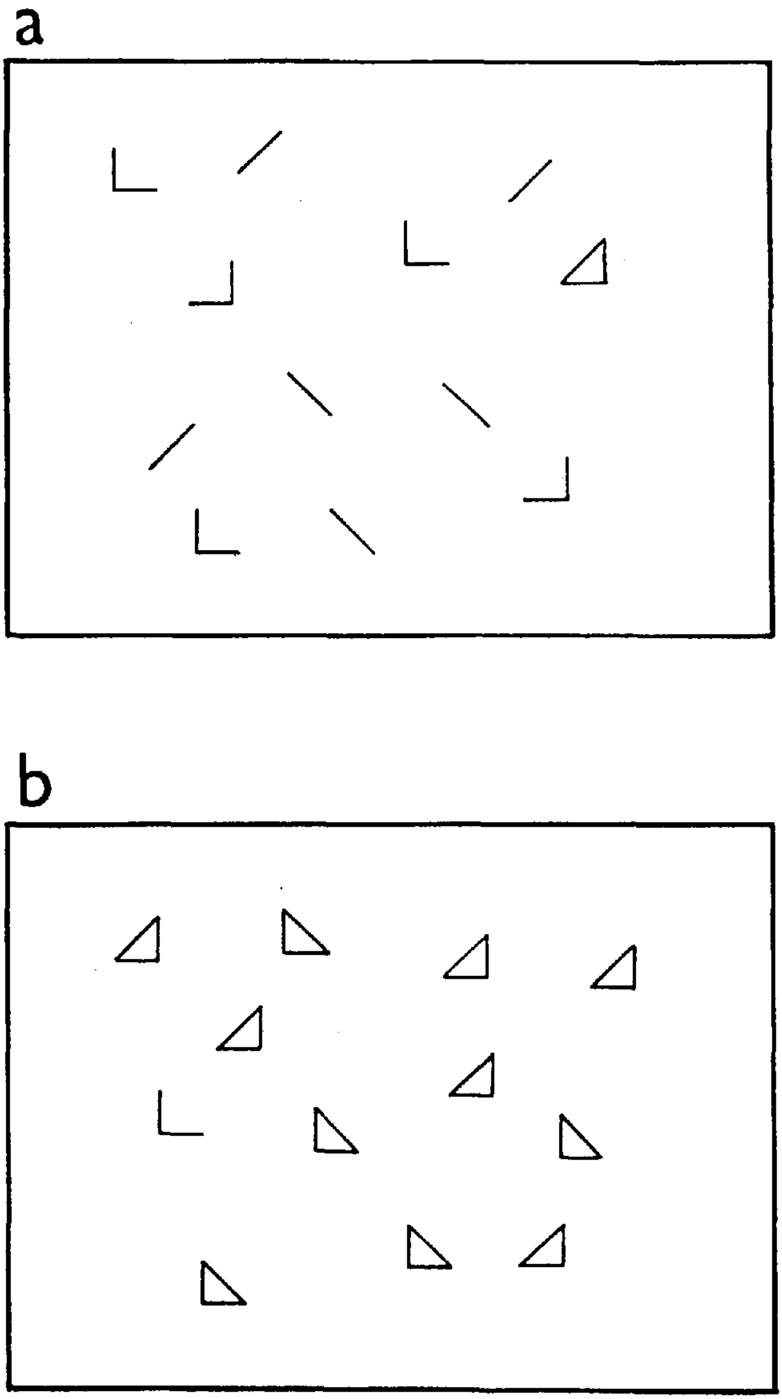

Figure 4. Examples of displays in the triangle presence and absence conditions of Experiment 3.

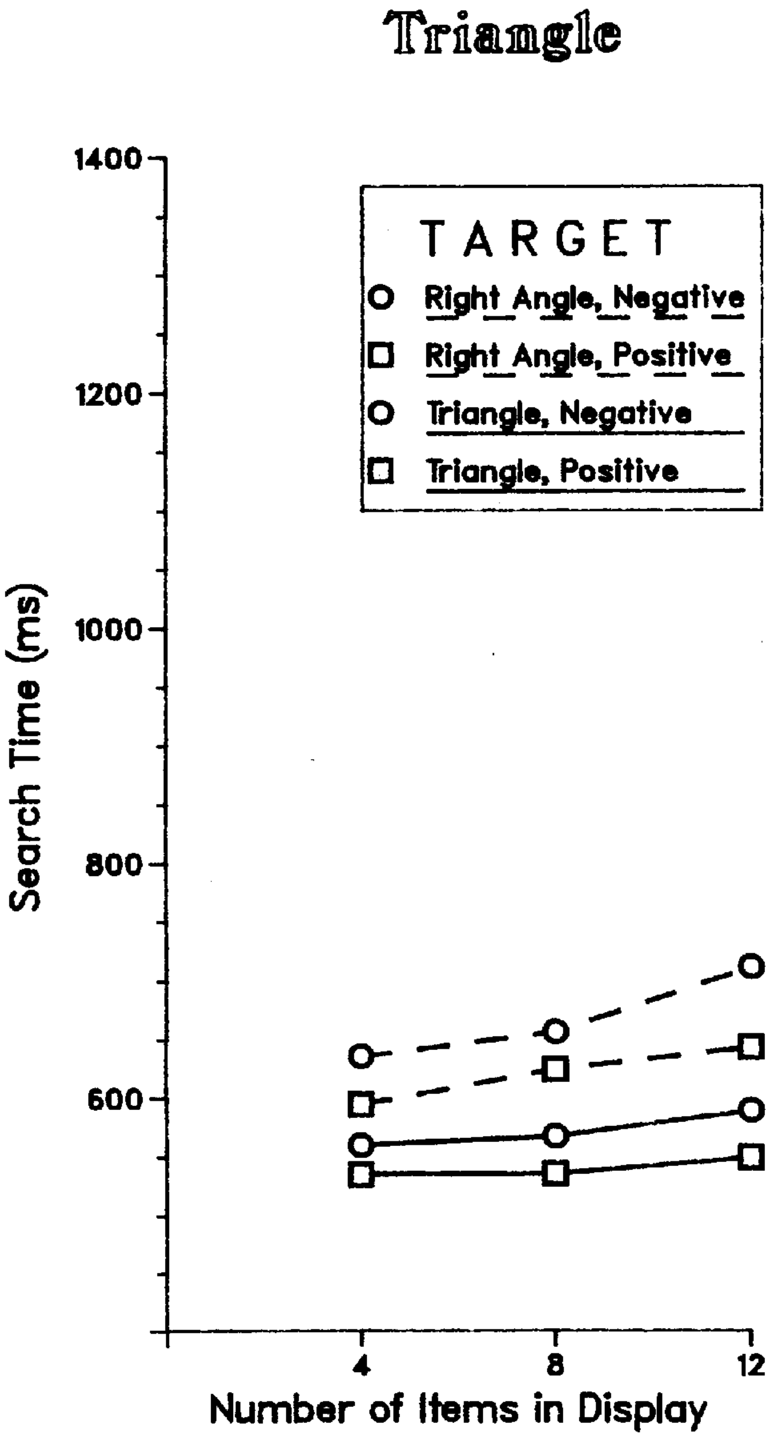

Figure 5. Search times in Experiment 3.

for positives and 3.8 for negatives. Heterogeneity of triangle or right angle orientations had no significant effect. If our arguments are correct, the result implies that the triangle has a primitive feature which is preattentively detected and which is not present in the angles and lines.

The results with the nontriangle target (right angle) were unfortunately less clear. Display size again had a significant effect, $F(1, 16) = 23.70$, $p < .001$. Search was significantly slower than search for the triangle target, $F(1, 16) = 7.31$, $p = .016$, and the difference interacted with display size, $F(2, 32) = 6.60$, $p = .004$. However, the slope was much less than the feature-absent slope with the shape and line displays of Experiments 1 and 2, averaging only 6.1 and 9.5 ms per item for positive and negative displays, respectively. Notice that a right angle can actually be described as a triangle without one line, logically equivalent to the circle without a line. It seems, however, that the removal of a triangle line, at least for some subjects, leaves a stimulus with a positive feature which can be detected preattentively. The implication may be that both a triangle and an angle have different and complementary primitive features, perhaps closure for the triangle and free ends or terminators for the right angle, analogous to green on the one hand, and red or black on the other. However, the free ends of the angle appear, at least in this context, to be detected somewhat less readily than the closure of the triangle. Perhaps the acute angle vertices of the triangles also partially activate the free-end detectors, making the free ends of the right angle target less distinctive and unique. In Experiment 4, we attempt to clarify further the question of the existence of free-end detectors, which remains tentative in relation to the data described so far.

Experiment 4: Circles With Gaps: Line Ends Are Features and Connectedness Is Not

Because the triangle condition of Experiment 3 left some ambiguity whether line ends function as a preattentively detectable feature, we attempted to clarify their status in a further experiment. This time the displays contained circles with and without gaps. In one condition, the target was a circle with free ends (a gap) in a display of circles without gaps; in the other condition, the target was a complete circle with no gap in a display of circles with gaps. The tasks could be defined in two ways: as search for the presence or for the absence of line ends, or as search for the presence or absence of closure (a closed circle). In this experiment, we also tested the effect of feature discriminability on search for presence and absence, by varying the size of the gap. Line ends are, in a sense, a categorical or discrete feature; if the size of the gap is above threshold, they are either present or not. If the presence of a gap is coded by the detection of line ends, their spatial separation should have little effect on search. Closure, on the other hand, can be defined perceptually in two different ways. By one definition, it is synonymous with connectedness, which is the inverse of free ends and categorical in the same way. By another definition, however, it could be a graded feature, depending on the degree to which an area is enclosed by a convex contour.

Method

Stimulus displays. The displays were presented on cards in a two-field Cambridge tachistoscope. The stimuli were drawn in black ink with a Staedtler-Mars Pocket template 977 115 GP. The 11.1-mm circle was used for all stimuli. Six sets of cards were made: In three sets (the *gap presence* sets), the target was a circle with a gap and the distractors were complete circles, and in three sets (the *gap absence* sets), the target was a complete circle and the distractors were circles with gaps. The three sets within each target-distractor combination differed in the size of the gap: In one, it was $^1/_8$ of the circumference, in another it was $^1/_4$, and in the third it was $^1/_2$ the circumference. The location of the gap was varied haphazardly. Figure 6 gives examples of the displays containing circles with $^1/_8$ and with $^1/_2$ gaps.

The stimuli were all contained in a rectangular area of $9.5° \times 13.1°$; the circle diameters subtended 1.5° at a viewing distance of 42 cm. Within each of the six sets of cards, three display sizes were used, 1, 6, and 12 items per card. The stimuli were haphazardly placed within the display area, except that the target appeared once in the inner and once in the outer area of each quadrant for each display size in each set, and so did the single distractor in negative displays of one item. There were eight cards of each type and each display size with target present and eight cards with target absent. The combinations of target and no target, three display sizes, three gap sizes, and two target-distractor combinations (presence and absence of gap) gives a total of 288 cards.

Subjects. Eight subjects (5 women and 3 men) were run in all conditions. They were students at UBC, who volunteered for the experiment and were paid $4 for each of two 1-hr sessions.

Procedure. The displays were presented in a Cambridge two-field tachistoscope. A central fixation dot was present between trials. On each trial the experimenter said *ready* and triggered the display, which remained visible until the subject responded by saying *yes* or *no*. The onset of the display also started a digital timer which was stopped by the vocal response through the Gerbrands voice-operated relay.

There were two main conditions in the experiment: search for a circle with a gap and search for a regular circle. These were run in separate blocks. All other conditions (gap size, display size, positive or negative display) were randomly mixed within the blocks of 144 trials. Subjects were given two blocks in each condition for a total of 576 trials, with the order of conditions counterbalanced across subjects. They later returned for a second session in which they repeated the complete experiment, reversing the order of target types.

Subjects were told before each condition what the targets and the distractors would be and were shown examples of each. The targets were defined as either "a circle with a gap, regardless of gap size, in a background of complete circles" or "a complete circle in a background of circles with gaps." Subjects were asked to decide as quickly as possible whether a target was present in each display or not and to say *yes* or *no*, accordingly. They were given about 20-practice trials before each condition and were given feedback on their errors throughout the experiment. They took a 5-min break between blocks.

Results and Discussion

Figure 7 shows the mean search times in each condition, and Table 2 shows the best-fitting slopes, intercepts, and the mean percent of the variance due to display size which could be attributed to linearity. Error rates were below 4% except for display size 12 in search for the complete circle, where they reached 8.2% on positive trials, representing missed targets. Table 3 shows the results of an ANOVA on all the data. The slopes did not differ significantly as a function of the order in which the decks were run; the overall means for Session 1 on the complete circle target were 31.2 and 27.3 ms per item for subjects who did that condition first and second, respectively, whereas the corresponding means for the circle with gap were 5.5 and 6.9. Thus there is no evidence that the reversed mapping gave rise to any substantial negative transfer in either case.

Again we find a striking asymmetry in the difficulty and in the strategy of search, depending only on which roles (target or distractors) the same two stimuli are allocated. When the target was a circle with a gap, search was fast, independent of gap size and little affected by display size, although the effect of display size was significant, $F(2, 14) = 36.4$, $p < .001$. The means of positive and negative slopes were 4.8, 4.7, and 5.3 ms per item for the largest to smallest gap sizes, respectively. There was no effect of gap size

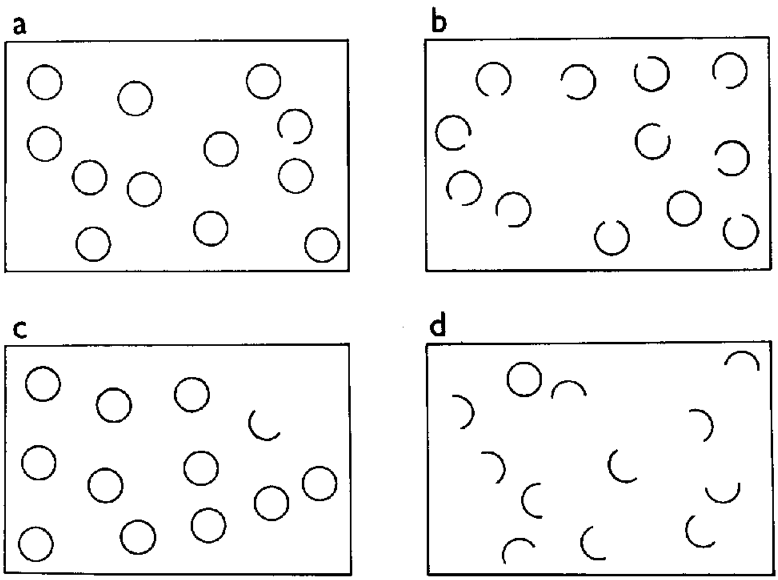

Figure 6. Examples of displays with target circles, and target circles with gaps at the largest and smallest gap sizes in Experiment 4.

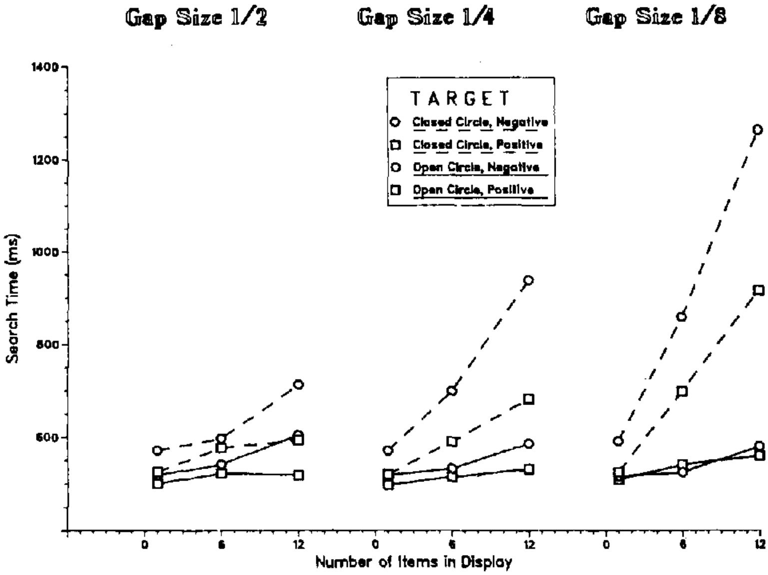

Figure 7. Search times in the different conditions of Experiment 4.

on the rate of search (i.e., no interaction between gap size and display size) and only a small, nonmonotonic effect on overall latency, $F(2, 14) = 4.9$, $p = .024$; the intercepts averaged 503, 501, and 506 ms. The data suggest that the presence of the gap is detected categorically, perhaps because the line end or terminator feature pops out of the display.

On the other hand, when the target was a closed or connected circle, search appeared

Table 2
Measures Relating Search Time to Display Size in Experiment 4

Performance measure	Slope	Slope ratio	Intercept	% Variance due to linearity
		Target: Gap		
Large gap (1/2)				
Positive	1.6	5.00	503	54
Negative	8.0		504	95
Medium gap (1/4)				
Positive	3.1	2.03	495	100
Negative	6.3		506	93
Small gap (1/8)				
Positive	4.7	1.28	508	96
Negative	6.0		503	89
		Target: No Gap		
Large gap (1/2)				
Positive	6.2	2.11	526	89
Negative	13.1		544	91
Medium gap (1/4)				
Positive	14.8	2.26	505	100
Negative	33.5		524	99
Small gap (1/8)				
Positive	33.6	1.82	488	100
Negative	61.3		516	100

Table 3
ANOVA on Results of Experiment 4

Factors	*F*	*df*	*p*
Target (presence or absence of gap)	89.0	1, 7	.001
Gap size	52.9	2, 14	.001
Display size	45.7	2, 14	.001
Positive or Negative Display	16.2	1, 7	.005
Target/Gap size	42.6	2, 14	.001
Target/Display size	40.7	2, 14	.001
Target/Positive or Negative	34.5	1, 7	.001
Gap size/Display size	25.1	4, 28	.001
Gap size/Positive or Negative	7.9	2, 14	.006
Display size/Positive or Negative	18.0	2, 14	.001
Target/Gap size/Display size	28.1	4, 28	.001
Target/Gap size/Positive or Negative	13.7	2, 14	.001
Target/Display size/Positive or Negative	14.8	2, 14	.001
Gap size/Display size/ Positive or Negative	2.3	4, 28	*ns*
Target/Gap size/Display size/Positive or Negative	8.0	4, 28	.001

to be serial, its rate strongly affected by the size of the gap in the distractors. When the gap size was medium or small, the functions relating search time to display size were linear and the slope ratio was close to 2.0. The speed of the serial search was strongly affected by the size of the gap, as if each item were checked faster or more slowly depending on the degree of closure. The implication within our suggested theoretical framework is that the closed circle lacks any unique distinctive feature which can be preattentively detected by the perceptual system.

When the distractors were semicircles (largest gap size), the results were less clear, at least for the positive displays: the function is almost flat between displays of 6 and 12, as if the closed circle target now sometimes popped out without a serial search. In a replication of the two conditions with the largest gap size (semicircles) in an experiment that excluded the conditions with smaller gap sizes, the slopes were even flatter: 3.2 for positives and 11.8 for negatives with the circle target; 3.3 for positives and 3.5 for negatives with the gap (semicircle) target. Here the positive slopes were identical for presence and absence of gap, suggesting that both the gap and the complete circle have distinctive features. The negatives, however, were slower and the function linear for the complete circle target.

How do we reconcile the slow serial search for a closed circle among circles with $\frac{1}{8}$- and $\frac{1}{4}$-sized gaps with the finding in Experiment 3 that triangle targets pop out of displays containing angles and lines? First, the new results confirm that the triangle was not detected by the absence of free ends, because the complete circle target also differed from the circles with gaps in having zero instead of two line ends or terminators. Second, they show that the relevant target feature in the triangle displays was not the connectedness of the outer contour. In this categorical sense of the word, closure does not seem to be preattentively available. Thus neither Julesz nor we were correct in our earlier suggestions. The triangle target must differ from the angles and lines in some other simple feature.

Another distinctive characteristic of the triangles in the displays of Experiment 3 was their acute angles. It seemed important to test whether this might be the feature mediating pop-out of the triangle targets, because an earlier article (Treisman & Paterson, 1984) had given an important theoretical role to closure in explaining several other results with triangles. Experiment 5 investigates search for acute angle targets among right angles and lines, to see whether this produces the same flat functions that we obtained with triangle targets in Experiment 3. The question is also of more general interest in testing a plausible candidate for a primitive visual feature. Angles are important in defining the shape and the three-dimensional orientation of rectilinear objects.

Experiment 5: Search for Acute Angles

Method

Stimuli. The distractors in this experiment were the same right angles and diagonal lines as those used in the heterogeneous condition of Experiment 3, with triangle targets. The targets were acute angles instead of right angles; more specifically, they were the triangle targets used before but with the base removed in one deck and with the vertical side removed in the other deck. Thus, they shared their component lines with the distractors, but were unique in having them conjoined to form an acute angle. In addition, they were no longer closed shapes like the triangles.

Twelve displays of 1, 6, and 12 items were made with the target with base missing (6 for each orientation), and 12 for each display size with the target with vertical side missing. The target locations were counterbalanced as before. In addition, 24 non-target displays were made for each display size (1, 6, and 12 distractors).

Subjects. Eight subjects, 4 men and 4 women, were run in this experiment. They were all students at UBC, who volunteered and were paid $4.00 an hour.

Procedure. The two target types, base missing and vertical side missing, were run in separate blocks. Each subject was given 30 trials of practice with each set before completing 3 blocks of 72 trials each (12 trials at each display size for target present and for no target displays). The order of the two target types was counterbalanced across subjects, and all other variables were randomly mixed within blocks. Otherwise, the procedure was the same as in the earlier experiments.

Results and Discussion

The mean search times and error rates are shown in Figure 8, together with the corresponding means for the heterogeneous triangle targets in Experiment 3. With the acute angle targets, there is clearly a substantial and significant effect of display size (averaging 19 ms per item on positives and 28 ms per item on negatives), whereas with the triangle targets there was almost none (a slope of only 2 or 3 ms per item). With acute angle targets, the effect of display size was significant, $F(2, 14) = 44.17$, $p = .001$. There was also a significant effect of acute angle type, $F(1, 7) = 8.74$, $p = .02$; the ones with vertical side removed gave slower search times than the ones with base removed, and also steeper slopes against display size (means 23 and 33 ms per item compared to 13 and 26 ms per item).

There are two points of interest: one is the inference we can draw about the way the visual system codes acute angles, and the other represents a clarification of the results with triangle targets. First, the data give no evidence that acute angles are coded preattentively and in parallel. By this criterion, they do not appear to function as perceptual primitives in visual analysis, distinct from right angles and diagonals, but rather as conjunctions of their component lines which must be serially located and checked with focused attention.

Second, the substantial increase in search times for acute angle targets with increases in display size appears to rule out the possibility that the parallel preattentive detection of triangle targets is mediated by feature detectors for acute angles. Some other characteristic of the triangles must allow them to pop out of the right angle and diagonal line distractors. We return to closure, then, as the most likely property mediating early parallel detection of triangles. However, in order to retain this hypothesis, we must redefine the term, clearly distinguishing it from connectedness. The relevant sense of closure may be the second sense that we defined earlier—the

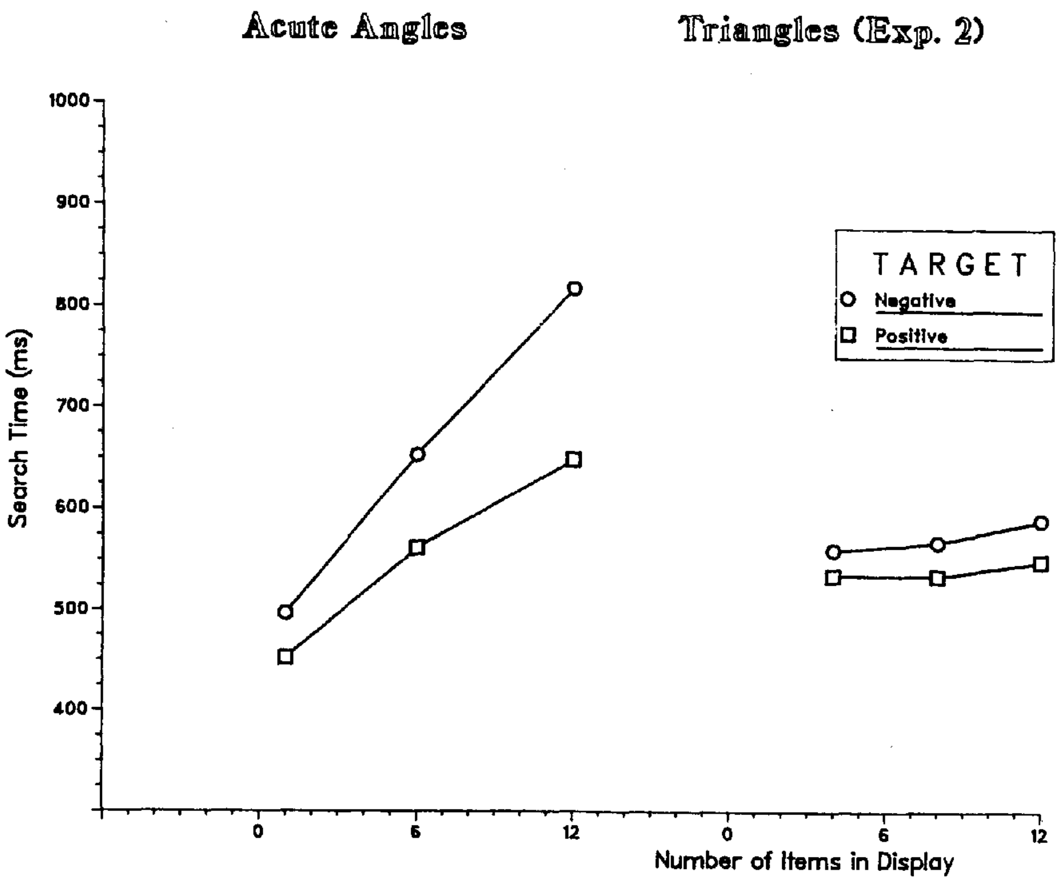

Figure 8. Search times in the different conditions of Experiment 5. (Exp. = Experiment)

sense in which it characterizes an area which is either partly or wholly surrounded by a convex contour. In this sense the feature is a graded one, which should mediate categorical pop-out only if the distractors totally lack it, and not if they possess it to some degree but quantitatively less than the target. It is interesting that, in Experiment 4, gap size had little effect on gap detection and a marked effect on closed circle detection, because this suggests the use of a graded feature in the latter case and a categorical feature in the former. The complete circle begins to emerge preattentively when the gap size is large enough to reduce the distractors to semicircles; perhaps the closure detectors begin to respond only when the length of the convex contour is substantially more than (perhaps double) the distance between the free ends. For a right angle the ratio is 1.41:1; for a semicircle it is 1.57:1; for a $^3/_4$ circle it is 3.33:1. The right angle distractors in triangle target displays, may be below the threshold to activate closure detectors at all, so that the triangle differs categorically from the angle and line distractors. The semicircle distractors have some minimal effect on the closure detectors, so that the complete circle target occasionally fails to pop out categorically. Closed circles differ from circles with smaller gaps along this closure–convexity dimension only in degree, and therefore preclude feature presence pop-out.

General Discussion

We have found several pairs of items, apparently differing in some simple physical property, in which large asymmetries appear in search, depending on which item is assigned the role of target and which the role of distractor. Can we use the results to throw light on the nature of visual features? First, we established that search for the presence of an added feature defining the target is faster than search for its absence, and in fact appears to be parallel, whereas search for its absence is serial. A single experiment cannot pin down what the added feature is in any particular case. In the circle with line experiment, it could be the line as a part, or it could be a property of the line (e.g., straight or vertical) or a property of the circle–line combination (e.g., intersection or angle). However, the results do establish that the circle without a line does not have a preattentively detectable feature that distinguishes it from circles with lines (e.g., intactness, emptiness, global symmetry). Note that it could have many other preattentively detectable features distinguishing it from other stimuli such as squares, ellipses, crosses and so forth. This is not the issue. Our conclusions are simply that search for the absence of a feature is serial, and that the absence of an intersecting line is not spontaneously recodable as the presence of some other feature. The experiment also establishes that search for absence cannot be based on parallel localization of multiple instances of a feature, allowing the one item without the feature to emerge by default. This strategy does not seem to be an option; serial search is required.

In order to determine precisely what the functional feature of the circle with line is, further experiments will be needed. For example, in one follow-up study we added separate vertical lines as distractors in addition to regular circles in displays with the circle and line target. If the relevant feature had been the line as a whole or any property of the line alone, the added distractor lines should preclude its use and force serial search. In fact, we again obtained pop-out for the circle–line target. This indicates that the feature is likely to be an emergent feature of the circle–line conjunction, for example, angles or intersection. By adding further candidates as distractors, we may be able finally to narrow down onto a single feature. Another example of this narrowing down procedure is the rejection of acute angles as the relevant target feature for triangle pop-out. However, we should bear in mind that subjects may switch which feature they use as they go from one type of display to another. For example, they could in the original circle and line displays have used vertical, but then switched to intersection when other vertical distractor lines were added. In general, negative results on pop-out may be more informative than positive results in that they tell us that no feature is present; thus a single experiment can potentially rule out many candidates for visual primitives, whereas it is difficult for a single experiment unambiguously to rule one in.

We next tested search for a feature (green) which is likely to be substitutive, and found no presence–absence asymmetry. Both green and nongreen targets were detected in parallel. This rules out the possibility that the asymmetry is related to the negative verbal definition of the target (e.g., "not green" or "no line"). Instead, it is consistent with the idea that pop-out depends on the presence of a target feature which is unique in the display, whether this feature is known in advance or disjunctive (e.g., "not green" implied "red or black").

We have argued from the results with the line and with the color stimuli that the observation of a presence–absence asymmetry can be used to define for a given pair of stimuli which aspect of the difference between them is positively coded by the visual system and which is not (perhaps analogous to a marked versus an unmarked linguistic feature). We can then apply this diagnostic to new tasks, as we did, for example, with the connectedness versus free-ends pair. The results showed a large asymmetry, favoring the conclusion that free ends are preattentively available features and that connectedness of contour is not. The visual system appears to represent the distinction between a complete circle and a circle with gap differently depending on which is the target. Other researchers have shown that the features of the target which are selected to control performance differ for different sets of distractors (Rabbitt, 1967). Here we extend that finding to show that for the same pair of stimuli, the features used differ for different target–distractor roles. We inferred also that the presence of free ends is not a substitutive feature in the language of visual coding; that is, to say, its removal does not imply its replacement by another preattentively available feature. Although the removal of free ends logically implies connectedness (if any contour remains present), connectedness appears not to be psychologically coded as such in early vision. Other aspects of the results are consistent with this inference: gap size had a large effect on search for the complete circle but not on search for the gap, as if a graded property is analyzed in the former case (perhaps degree of closure) and a categorical one in the other (free ends).

The results suggest two kinds of visual code in early vision: (a) sets of *substitutive* features, which either form dimensions of variation or function simply as feature pairs for which the removal of one creates its converse and both are positively coded features and (b) *single positively coded* ("marked") features, whose absence from individual stimuli (among others in which they are present) can only be detected by the negative strategy of serially checking each stimulus for the presence of the feature and eventually responding by default to its absence.

There is, in the literature on similarity judgments, an interesting asymmetry that seems potentially relevant to our results. Rosch (1975) and Tversky (1977) showed that subjects judge a less salient, less prototypical, or less complex figure as more similar to a salient, prototypical, or complex figure than the reverse. For example, an ellipse is judged more similar to a circle than a circle is to an ellipse, and an *F* is more often confused with an *E* than the reverse. Tversky attributes this asymmetry to the relative salience of the features in the two figures; the distinctive features of the more salient figure are given greater weight in determining dissimilarity. It is tempting to apply this idea to the search task, but it is not immediately obvious how to do so. There are two difficulties: first it is not clear whether subjects in a search task detect a target because it contrasts with the distractors that surround it, or conduct the search by comparing display items to a stored representation of the target. Secondly, the various criteria Tversky suggests for determining which stimulus is more salient may conflict, and for some of our stimuli appear to do so. The intact circle is more prototypical than the circle with a line or a gap, but it is also less rich and complex; it certainly has fewer features. The complete circle includes the circle with the gap, but could also be said to lack one of its additional features. Given these ambiguities, we can find an interpretation which is consistent with our results in each case: we could say that the regular circle is more similar to the circle with the line, because the latter is more complex and includes the former. In this case, we must infer also that subjects compare the target to the distractors, in order to predict the observed result that search is easier when the circle with the line is the target. Alternatively, we can say that the circle with the line is more similar to the prototypical regular circle; in this case we must assume that the distractors are compared to the target, in order to predict the observed result. Although in each case we can account for a difference in difficulty, neither pair of assumptions explains the observed change from parallel to serial processing for the more difficult condition.

The discussion so far has focused on the general logic of the method and its use to throw light on functional features. In the next section we discuss a possible model which could account for our findings. The general conclusions outlined here do not depend on the plausibility of the specific model we propose.

The hypothesis we suggest to account for parallel search and presence–absence asymmetries is that perceptual features are separately registered in different maps (see Figure

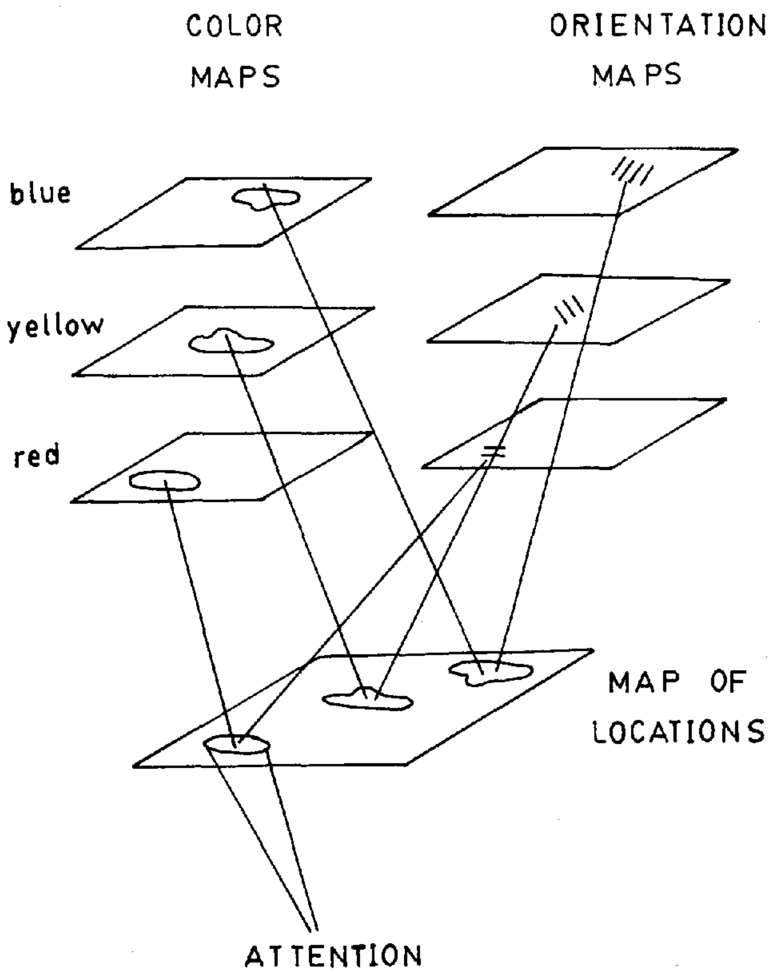

Figure 9. Schematic diagram suggesting the functional arrangement of feature maps and master location map through which attention links features to form objects.

9). When a set of features constitutes a perceptual dimension, there may be a related set or continuum of these maps to represent the dimension. Thus, different orientations would be represented by points in a three-dimensional stack, two of whose dimensions represent spatial location in the frontal plane (or perhaps on the retina), whereas the last represents the dimension of orientation (vertical through intervening angles to horizontal) with adjacent orientations also adjacent in this dimensional representation. The structural anatomy of visual areas mapped by Hubel and Wiesel (1968) is consistent with such an arrangement. Similar arrays of maps could represent adjacent colors in an orderly progression, and also other perceptual dimensions such as the direction of motion and stereo depth.

We further assume that, in order to retrieve location information from these maps, or to relate locations across maps, focused attention is necessary. The information which can be retrieved without focused attention is simply the presence and the amount of activity in any given prespecified map. This can be categorical—there either is or is not activity, representing the presence or absence of the feature in question in the visual display—or the activity can be graded, representing the degree to which the feature is represented in the display as a whole. This pooled measure of activity is analogous to a Hough transform, which has been used in recent parameter net models of early vision (e.g., Ballard, 1981).

Figure 9 shows a crude representation of two separate modules which analyze colors and orientations, respectively, into ordered stacks of feature maps. A possible implementation of spatial attention could be through connections to a master map of locations, in which the positions of any discontinuities in stimulation are coded without specific information on the nature of the discontinuity. Spatial locations in all the separate feature maps may be accessed by their links to this master map. The attentional "spotlight" would act by serially selecting particular active locations in the master map, thereby automatically retrieving all the features in the separate feature maps which are currently linked to those locations. Any features currently accessed by the attentional spotlight would be conjoined and perhaps transferred to short-term storage, allowing correct identification of the objects from which they originated. Because attention can also be guided by preattentively detected features (e.g., we can scan and report only the red items in a display containing other distractor colors), we must assume that any given feature map can also selectively index locations containing the relevant feature in the master map. Attention must, however, scan these locations serially to link them to the features in corresponding locations in other maps. Serial search for feature absence is thus explained by the same assumptions previously used in feature-integration theory to account for serial search in conjunction tasks (Treisman & Gelade, 1980).

If the nonspatial dimension varies continuously rather than categorically (e.g., color, size, brightness, orientation), it may be possible to select a slice of the cube rather than a single layer, just as attention can also select a spatial group of items to check in parallel (Treisman, 1982). Thus search for a red, orange, or yellow target in a background of green and blue may not be much harder than search for a single color (e.g., red). Selecting two discontinuous slices may, however, require more time; thus search for blue and yellow in a background of red and green may require two operations rather than one, just as spatial attention must be focused serially on separate items when these are spatially intermingled with irrelevant items. Julesz (1975) showed that texture segregation is possible when spectrally adjacent colors are grouped, but not when the spatial grouping is of spectrally interleaved colors. Mixed red and yellow items segregate well from mixed green and blue ones, but mixed red and green items do not segregate perceptually from mixed yellow and blue ones.

In visual search tasks, then, we suggest that two different strategies are available: (a) to inspect a feature map and to detect categorically the presence or absence of activity anywhere in that map, or perhaps to discriminate between two clearly different overall levels of pooled activity. This strategy can be used when the target has a distinctive, preattentively detected feature which the distractors do not share, or which the distractors possess to a lesser degree. The search in this case is parallel or global, over the display as a whole, and the target will pop out. (b) When target features must be localized (i.e., when the target is defined by the absence of a feature or when the target and the distractors differ only quantitatively on the relevant dimension), then we suggest that focused attention and serial scanning are required. Latencies show a linear relation to display size, with a 2:1 ratio of slopes on negative and positive displays.

We have found large differences in slopes across different conditions, in all of which search appeared to be serial and self-terminating. For example in Experiment 4, the rate of scanning for closed circle targets varied dramatically with the gap size of the distractors. Two explanations seem possible. So far we have attributed the differences in slope to the idea that the more discriminable each distractor is from the target, the quicker it can be rejected in the course of serial scanning. However, the scanning rates in some conditions would be very high if this were assumed to be the only variable (as little as 13 ms per item for closed circles among distractors with the largest gap size).

An alternative account can be proposed if one considers the effects of target–distractor discriminability on the level of pooled activity among feature detectors. Suppose that the relevant feature distinguishing the target from the distractors is shared by both, but they possess it to differing degrees. For example, the target might be more "closed" than the distractors. The pooled response to displays containing one target will differ from the pooled response to displays containing only distractors by the same fixed increment or decrement, regardless of the number of distractors. According to Weber's Law, however, this fixed difference should have a larger impact at low levels of background activity (few distractors) than at high levels. For example, if the target produces 5 units of activity in one particular feature map, and each distractor produces 1 unit of activity in the same map, then target and nontarget displays of one item will differ by a ratio of 5:1 (or 5.0); displays of 6 items will differ by a ratio of 10:6 (or 1.67); and displays of 12 items will differ by a ratio of 16:12 (or 1.33). If discriminability depends on these ratios, it will be much greater for small than for large displays. In this case, subjects may serially scan small groups of items within the large displays rather than serially scanning individual items, choosing a group size small enough to ensure that groups containing a target differ reliably from groups containing only distractors in the pooled measure of activity within the group. For example with a group size of two items and the 5:1 difference in feature strength assumed earlier, a group containing a target with the relevant feature would produce 6 units of activity and one containing only distractors would produce 2 units. This difference might be discriminable, whereas the difference over the whole display of 12 items (16 versus 12 units of pooled activity) would not.

By the same reasoning, search for absence using the pooled activity measure should suffer bigger decrements in discriminability with increases in the number of items than should search for presence. For example, if the distractors produce 5 units of activity in the relevant feature map and the target produces only 1 unit, the pooled activity ratios for target to nontarget displays of 1, 6, and 12 items, respectively, will be 1:5, 26:30, and 56:60. Group size would need to be considerably smaller to meet the same criterion of accuracy when the target produces less activity than the distractors in the relevant feature detectors. Slopes should therefore be steeper in this condition than when the target produces more feature activity than the distractors, although search would be serial in both cases. It might be possible empirically to discover the group size a subject is using in any given search task by varying display size, starting at one item and increasing to two, then three and so on. The group size should be apparent as the inflection point at which display size first affects search.

How do the specific stimuli we have tested fit into this framework? We suggest that targets defined by either a unique color (green in other colors, or nongreen in green), or line ends (terminators), or an added intersecting line, fit pattern (1): a categorical presence or absence of the relevant feature (or of either of two relevant features, e.g., red or black). These targets pop out because they are detected preattentively by checking the overall pooled measure of activity within the relevant feature map. Closure, in the sense of a largely or wholly contained area among shapes that are open (e.g., triangle in right angles and perhaps circle in semicircles), also fits this pattern when the gap in the distractors is sufficiently large relative to the length of the convex contour. Finally, the shape without the line, the circle without the gap, and the acute angles, as well as the standard conjunction search (for example, a green *T* target in brown *T* and green *S* distractors) fit pattern (2), in which search must be serial and self-terminating because focused attention is required to locate the target. When the target and distractors differ only quantitatively on the relevant dimension (for example, closure for the circles with and without small gaps), their discriminability affects the rate of serial search. Subjects may serially check groups of items instead of individual items, adjusting the group size to meet a given criterion of accuracy.

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New Look for the APA Journals in 1986 and Change in Frequency for *JEP: Perception*

Beginning in 1986, the APA journals will have a new look. All the journals will be 8¼ × 11 inches—a little larger than the *American Psychologist* is now. This change in trim size will help reduce the costs of producing the journals, both because more type can be printed on the larger page (reducing the number of pages and amount of paper needed) and because the larger size allows for more efficient printing by many of the presses in use today. In addition, the type size of the text will be slightly smaller for most of the journals, which will contribute to the most efficient use of each printed page.

Also beginning in 1986, *JEP: Human Perception and Performance* will be published as a quarterly rather than a bimonthly. This change is a result of the change in trim size and consequent reduction in the absolute number of printed pages per issue and is not an indication that fewer articles are being published. It will also bring *Perception* in line with the other three *JEPs*, which are all quarterlies.

These changes are part of continuing efforts to keep the costs of producing the APA journals down, to offset the escalating costs of paper and mailing, and to minimize as much as possible increases in the prices of subscriptions to the APA journals.
