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Preattentive Object Files: Shapeless Bundles of Basic Features

JEREMY M. WOLFE,*† SARA C. BENNETT*

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A considerable body of recent evidence shows that preattentive processes can carve visual input into candidate objects. Borrowing and modifying terminology from Kahneman & Treisman (1984), this paper investigates the properties of these *preattentive object files*. Experiments 1–3 show that preattentive object files are loose collections of basic features. Thus, we can know preattentively that an object has the attributes "red" and "vertical" and yet have no idea if any part of the object is red *and* vertical. Experiment 4 shows that some information about the structure of an object is available preattentively, but Experiments 5–12 search for and fail to find any preattentive representation of overall shape. Appreciation of the overall shape of an object appears to require the binding together of local form features—a process that requires attention. Copyright © 1996 Elsevier Science Ltd

INTRODUCTION

In visual search experiments, observers look for a target item in a field containing a variable number of distracting items. These experiments are meant to mimic the natural visual task of looking for something that is present in the visible scene but somehow not fully processed by the viewer. For example, when you unfold the morning paper, the word "Congress" may or may not be present in the headlines. Let us assume that it is present. It is *visible* when you look at the page, but it is not *read* until you direct your attention to that specific word. This is true even if we assume that Congress has done something that merits a headline large enough to make the word readable in peripheral vision. A stimulus that is visible but unattended can be said to have been preattentively processed.

Quite a lot is known about preattentive processing. There is a large body of data showing preattentive processing of basic features like color, size, and orientation (see Treisman, 1986; Wolfe, 1994, 1996b for reviews). There is also evidence for the preattentive processing of form primitives like line termination (Julesz, 1984; Julesz & Bergen, 1983), closure (Donnelly *et al.*, 1991; Elder & Zucker, 1993, 1994); topological constraints (e.g. "holes"—Chen, 1990; Zhou *et al.*, 1992; Rubin & Kanwisher, 1985), and line intersections (Julesz, 1984, 1986; Julesz & Bergen, 1983). All of these are surrounded by some degree of controversy though there is wide agreement on the general idea of preattentive processing of form (see Bergen, 1991; Bergen & Adelson, 1988; and Julesz & Krose, 1988 on intersection, for example, or Cheal & Lyon, 1992 for a general look at the complexities of form features).

The subject of this paper is the preattentive representation of objects. What is known about an object before attention arrives? In order to address this issue, it is useful to distinguish between "shape" and "form". In this paper, the term "shape" will refer to the form of an object as a whole. "Form" will refer to local attributes. Thus, a "plus" might be said to have the overall shape of a plus while its form feature would include four local line terminators and an intersection. This distinction between the uses of "shape" and "form" relies on the notion of an object. Though object perception is an important topic in vision research, object is not an easy term to define. Indeed, textbooks with chapters on object perception generally just assume that we all know what is being talked about (e.g. Goldstein, 1996). For our purposes, an object is a numerable thing as distinct from a collection of numerable things and as distinct from unenumerable "stuff" (Adelson & Bergen, 1991). Thus apples and rabbits are objects. Sand and water are not. Such a definition is not entirely satisfying since an object such as a human being can be composed of other objects such as heads and hands. However, if we restrict ourselves to relatively simple objects like two-dimensional closed curves, the commonsense use of the term will do well enough. Restricting ourselves to two-dimensional figures in the frontal plane also puts off to another day the questions of viewpoint, self-occlusion, and so forth that arise with three-dimensional objects.

Using the terms in this way, two objects might share

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*Center for Ophthalmic Research, Brigham and Women's Hospital, 221 Longwood Ave, Boston, MA 02115, U.S.A.

†To whom all correspondence should be addressed at: Harvard Medical School, 221 Longwood Ave, Boston, MA 02115, U.S.A. [*Email* wolfe@search.bwh.harvard.edu].

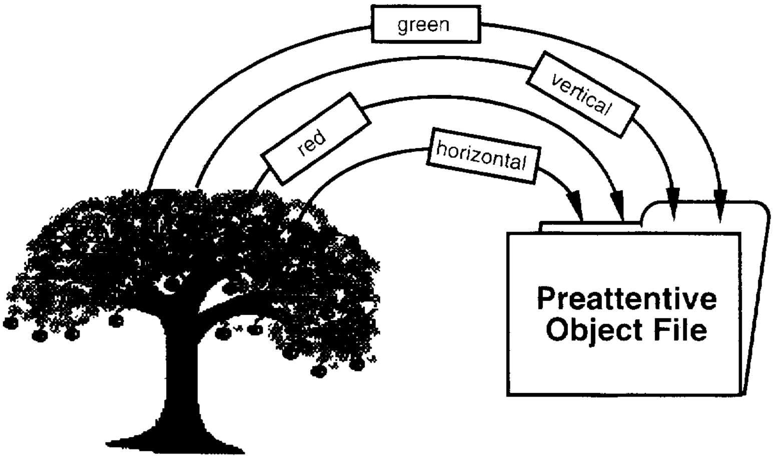

FIGURE 1. Preattentive object files.

the same preattentively available form features (e.g., two different objects might each have a hole, a line termination and an intersection—see Fig. 12). These objects could have other different shapes if the form features were arranged differently. While preattentive form has been studied, the preattentive processing of the shape of an object has not been the subject of systematic study. This paper will reach three main conclusions about the nature of the preattentive representation of objects:

1. The visual stimulus is divided into objects preattentively. The set of preattentive objects may not be identical to the set of objects found with attentional scrutiny, but some object-like entities are created preattentively.
2. These preattentive objects exist as receptacles holding local features, including form features. These features are unbound. That is, their relationship to each other is not made explicit until attention is directed to the object.
3. These preattentive objects are shapeless. While there is preattentive processing of form, the data presented here suggest that there is no preattentive information about the overall shape of an object.

Consider an apple tree. The argument of this paper is that, as a preattentively processed object, an apple tree would have features like "red", "green", "brown", "vertical", "big", "little", "line terminator", and, no doubt, several others. However, those features would exist as a list belonging to a *preattentive object file* (borrowing the term from Kahneman and Treisman's (1984) notion of an *object file.*). Preattentively, we would not know that brown goes with vertical nor that red goes with small round bits. Moreover, we would not know that this item was shaped like a tree. This information would become available only when attention took the contents of the preattentive object file and bound or integrated them into a perceived apple tree.* In the experiments reported below, simple objects will be used because an apple tree, like a human body, is a hierarchical object with parts (like apples and leaves) that can also be objects in their own right (Fig. 1).

Preattentive objects?

Before we can discuss the properties of preattentive objects, we need to examine the assumption that such objects exist at all. An alternative is that the preattentive representation of the visual world is just a collection of features in retinotopic maps. Thus, in the apple tree example, there might be "red" at location x,y and "small" at location x,y. "Space-based" attention directed to location x,y would be required to bind "red" and "small" into a single object. Using the terms of Kahneman & Treisman (1984), attention would create an object file to hold the resulting apple. The "object-based" idea that attention can select objects has been gaining ascendancy over "space-based" models during the last decade, but models of visual search have been slow to catch up (or have been agnostic on the topic). For instance, the most recent version of our Guided Search model (Wolfe, 1994) is an essentially space-based account of visual search.

Work from a number of laboratories using different attentional paradigms shows that attention can be directed to objects. Duncan (1984) had observers making judgments about properties of two overlapping objects. It was easier to make judgments about two properties of one object than about one property of each of two objects. This paradigm has been revisited by Vecera & Farah (1994). They replicated and extended Duncan's basic findings and concluded that both object- and space-based selection are possible. Baylis & Driver (1993) used different stimuli to make a similar point. They found that it was much easier to make a judgment about the

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*This conception is borrowed from Treisman & Gelade (1980). While we have disagreed with aspects of Feature Integration Theory (Wolfe, 1994; Wolfe *et al.*, 1989), we believe that Treisman correctly proposed that a central function of attention is to integrate features in a way that is simply not possible preattentively.

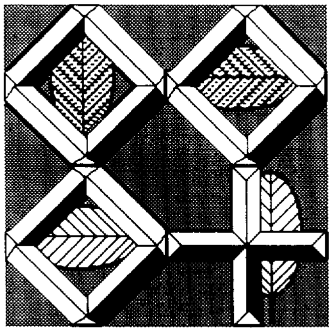

FIGURE 2. In the lower right-hand corner of this figure "horizontal" and "white" occur at the same spatial location. However, because "horizontal" and "white" are part of different objects, the spurious conjunction does not interfere with the search for a horizontal white leaf.

relationship of two properties of one object than about the relationship between properties on each of two (see also Baylis, 1994; Gibson, 1994). Arguing from a more theoretical perspective, Schneider (1993) also concludes that purely space-based accounts are inadequate.

One indication that attention has been deployed to an item or a location is that, after attention has moved on, there is an "inhibition of return". It is harder to attend to a recently attended location (Posner & Cohen, 1984; Nakayama & Mackeben, 1989). In several studies, there is evidence for inhibition in both space-based and object-based frames (Gibson & Egeth, 1994; Tipper *et al.*, 1991, 1994).

Turning to visual search tasks, Yantis and his colleagues have performed a series of experiments investigating stimuli that grab attention. Originally, they thought that abrupt onsets had a privileged ability to attract attention (Jonides & Yantis, 1988; Yantis & Johnson, 1990). However, in more recent work, Yantis has argued that it is new objects that capture attention (Yantis, 1993; Yantis & Gibson, 1994). If new objects capture attention, it would seem to follow that they are somehow represented as objects preattentively. Rensink & Enns (1995) did an experiment that also argues for the preattentive creation of something like an object. They show there are some aspects of the visual stimulus that cannot be accessed in visual search apparently because those attributes were suppressed in the creation of perceptual objects.

Most search experiments involve isolated items presented against a blank background. We have done a series of experiments using stimuli of the sort shown in Fig. 2. Here, objects can occlude one another, in this particular example, the "lattice" extended across the entire image. The leaf "objects" could be occluded by the lattice, breaking the image of the object and raising the possibility of "spurious conjunctions" of features. For example, at the location in the lower right of this figure, a horizontal bar of the lattice crosses the vertical, white leaf. At the point of occlusion, "horizontal" and "white" coexist. In a search for "white horizontal", purely space-based processing might be attracted to this location. Object-based processing would not be fooled by this spurious conjunction because "white" belongs to one object (the leaf) while "horizontal" belongs to another (the lattice).

Our data from experiments with stimuli of this sort indicate that visual search is not fooled by these spurious conjunctions and is only minimally disturbed by the occlusion of objects (Wolfe, 1996a). Thus, the accumulation of evidence indicates that the visual scene is divided into objects preattentively. Note that this does not mean that it is divided into the set of *perceived* objects. Preattentive object division might be inaccurate. It might create preattentive objects that we would not consider to be perceptual objects. It might miss objects. What seems clear is that some representation of objects is created prior to the application of attention.

If the scene is parsed into objects preattentively, what are the properties of those preattentive objects? The experiments presented here explore this issue. The results support the modification of Kahneman and Treisman's (1984) notion of an *object file* sketched above. In the original conception, an object file is a mental report created when attention arrives at a locus and binds the features together. In our new conception, a preattentive object can be thought of as an object file that is metaphorically similar to the file folders in your file cabinet. It looks like all the other file folders. What differentiates it from other files is its contents. We can imagine the image features to be those contents. Returning to the apple tree example, the preattentive object file would contain entries that say "This object has red", "This object has shininess*", "This object has vertical", "This object has right tilted contours" and so forth. Preattentively, an object's features are simply collected in the object file. The role of attention, in this metaphor, is to open the file and to properly bind the features together. Only when attention arrives, would the perceiver know if the red bit was shiny. This account implies that there is no preattentive difference between a tree with shiny red apples and matte green leaves and a tree with matte red apples and shiny green leaves. Both would create preattentive object files containing red, green, shiny, and matte. Experiments 1–4 support this hypothesis.

One candidate attribute that might be stored in the preattentive object file is the overall shape of the object. Most of the "shape" experiments done to date involve other features. For instance, "X"s and "O"s may be different shapes but an "X" is also differentiated from "O"s by the basic features of curvature (Treisman & Gormican, 1988; Wolfe *et al.*, 1992b), line termination, and intersection. When all of the dozen or so other basic features are controlled for, is there evidence for preattentive representation of the overall shape of an object? Experiments 5–10 look for evidence and find none. This finding has the usual problem of negative

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*Shininess is a preattentive feature (Wolfe & Franzel, 1988).

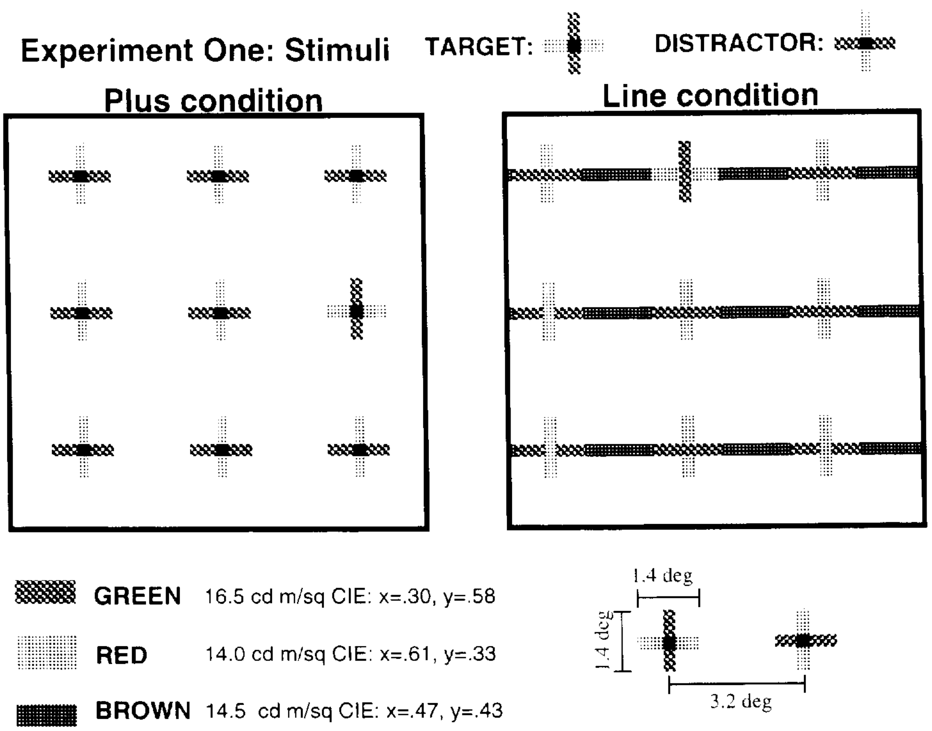

FIGURE 3. Stimuli for Experiment 1.

evidence. However, the assertion that there is no preattentive representation of overall shape can be used to generate specific, falsifiable hypotheses. For example, it should be the case that two shapes will not be preattentively discriminable if they have the same set of local form features, even if those features are put together to form very different shapes. Experiment 11 provides evidence in support of this prediction.

EXPERIMENT 1: THE CONTENTS OF THE PREATTENTIVE OBJECT FILE

As noted, apple trees are a bit complex for visual search experiments. Much simpler stimuli were used in Experiment 1 and are shown in Fig. 3. The target is a "plus" composed of green vertical and red horizontal segments. The distractors are composed of red *vertical* and green *horizontal* segments. Note that this is variation

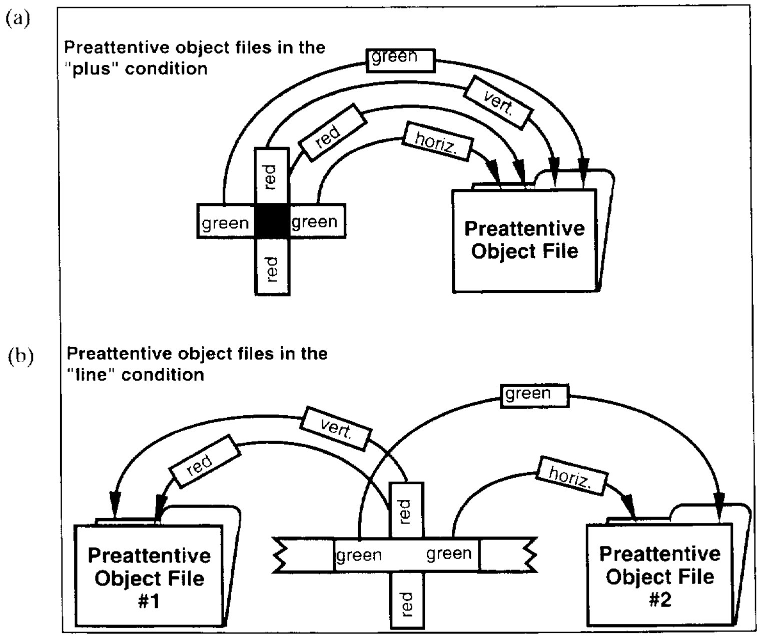

FIGURE 4. Hypothetical preattentive object files for a distractor object in Experiment 1.

on a standard conjunction search. Observers can look for a green vertical line among red vertical and green horizontal distractors—a color X orientation conjunction. In this version, observers also have the option of searching for a red horizontal line. Two conditions were run. In the "Plus" condition (4a), targets and distractors were plusses, each intended to look like a single object. According to the preattentive object file hypothesis, the target plus should be difficult to distinguish from the distractor plusses because, preattentively, the two types of plus are identical. Each would be represented as a file containing "red", "green", "vertical", and "horizontal" [Fig. 4(a)].

In the "lines" condition (4b), the horizontal segments of the plusses are joined by a brown line. The intersections were black. The intention was to promote an alternative division of the stimulus into objects; specifically, grouping of the horizontal segments so as to break apart the plus. According to the preattentive object file hypothesis, this could create two object files at each location: one containing the attributes of the vertical segment and the other containing the attributes of the horizontal [Fig. 4(b)].*

According to Guided Search (Wolfe, 1994; Wolfe *et al.*, 1989), efficient search for conjunctions is made possible by the combination of information from two or more feature processors operating in parallel across the visual field. In a search for a green vertical target in a color × orientation conjunction, for example, a color processor would guide attention toward all green items, while an orientation processor would guide attention toward all vertical (or "steep"—Wolfe *et al.*, 1992a) items. The combination of these two sources of guidance would tend to direct attention toward green vertical items even though neither parallel process alone could do so. In the "plus" condition of Experiment 1, this guidance mechanism is thwarted. If each plus is represented preattentively as {red and green and vertical and horizontal}, then all items are preattentively equivalent and no preattentive guidance is possible. By contrast, in the "lines" condition, if the plus is broken up, then the vertical element would become an object unto itself and it should be possible to guide attention to a green vertical element in the usual fashion.

Size and color information about the stimuli is provided in Fig. 3. Colors were set to near isoluminance by flicker photometry.† Stimuli were presented in square arrays of 9, 16, or 25 items. Items were evenly spaced to allow the horizontal line segments to be joined together in the "lines" condition. The 25 element, 5 × 5 array filled the entire 16 by 16 deg display area. Smaller displays were presented at random locations in the field. Since the stimulus was on until the observer responded, it is possible (indeed, likely) that observers made an eye movement to foveate near the center of the smaller arrays. This would tend to artificially lower RTs for the smaller arrays, thus artificially increasing the slope of the RT by set size functions in this experiment. Since this is true for both "plus" and "lines" conditions, it remains possible to compare the two conditions.

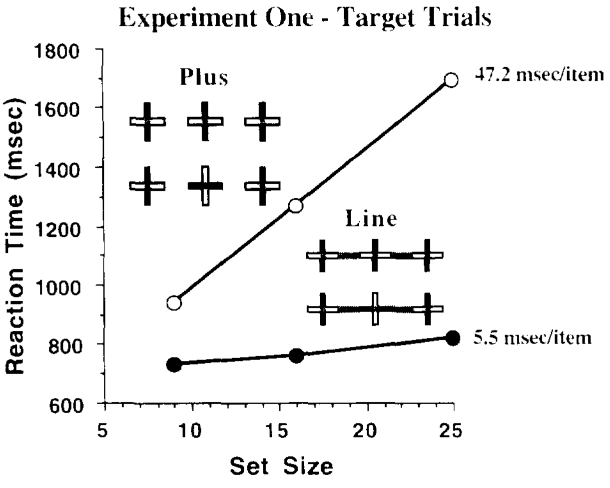

FIGURE 5. RT × set size functions for target trials in Experiment 1.

Observers were tested for 30 practice and 300 experimental trials in each condition. The order of conditions was counterbalanced across observers. Observers sat 57.4 cm from the screen of a MacII computer. Stimuli were presented and responses collected using VSearch software (Enns *et al.*, 1990). The index finger of one hand was used to make target present responses, while the index finger of the other hand was used to make target absent responses. Observers were instructed to respond as quickly as possible while making only a few errors (<10%). If a response was not made within 7500 msec, the trial was terminated and a time-out error was recorded. These were rare.

Observers

Ten observers between the ages of 23 and 45 yr were tested. All were volunteers from the local community who gave informed consent and were paid for their time. All had or were corrected to at least 20/25 visual acuity and all passed the Ishihara plates color vision screening test.

Results

Figure 5 shows results averaged across all observers. In this and all subsequent experiments, median reaction times were obtained for each observer at each set size. Use of the medians reduces the impact of RT outliers. The mean of those medians is plotted in Fig. 5 for target trial data only. It is clear that the "plus" condition produces a far less efficient search than does the "line" condition. This difference is significant by *post hoc* tests (Tukey, $P < 0.05$). Error rates were 4% in the "line" condition and 2% in the "plus" condition. Best-fitting

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*Presumably, the file containing "green" and "horizontal" would also contain the "brown" connecting the green segements.

†This is important since strong luminance cues seemed to make it possible to break apart the plusses. See Theeuwes & Kooi (1994) for a related point.

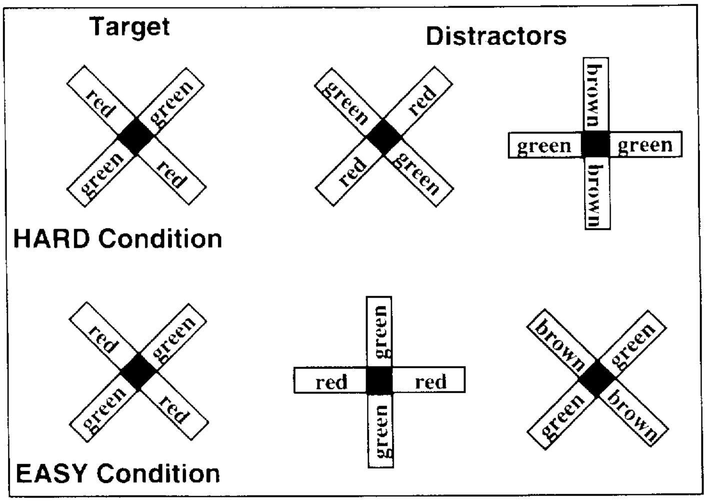

FIGURE 6. Stimuli for Experiment 2.

linear RT × set size functions for the blank (or "target absent") trials were 719 msec + 85.2 msec/item for the "plus" condition and 496 msec + 49.8 msec/item for the "line" condition. These steep blank trial slopes indicate that observers adapted a very conservative quitting criterion (Chun & Wolfe, 1996).

Discussion

The "plus" condition produced very inefficient search. The RT × set size slopes of 47 msec/item for target present trials and 85 msec/item for target absent trials are significantly steeper than the slopes for standard "serial" searches (Treisman & Gelade, 1980; Kwak *et al.*, 1991). This suggests that it took substantially longer than the usual 40–50 msec to inspect each item. Introspectively, this seems correct. It seemed to take some work to deduce whether the vertical or horizontal segments of the plus were red or green. The "line" condition was much easier. By connecting all of the horizontal line segments, it became possible to search efficiently for green vertical segments. Note that the same red and green pixels were present in both conditions and that both conditions are, in principle, simple conjunctions of color and orientation. If simple color × orientation searches are the appropriate comparison for these stimuli, then it could be argued that the appropriate set size is not the number of "plusses" but the number of vertical and horizontal line segments. This would double the set size and halve the slope estimates. The resulting slopes of 23 and 42 msec/item in the "plus" condition would still be consistent with a serial, self terminating search through all line segments and would not be consistent with the much more efficient search reported for standard color × orientation conjunction searches (Treisman & Sato, 1990; Wolfe *et al.*, 1989—and see Experiment 3). Apparently, something about the "plus" configuration made efficient search impossible. This is consistent with the idea that the plus stimulus is preattentively represented as "red", "green", "vertical" and "horizontal"—a preattentive object file with unbound features in it.

In the Line condition, the preattentive object files are different. Perhaps all of the colinear horizontal lines form a single, long horizontal item that is easily rejected as a target. This allows each vertical line segment to create an independent object file containing the attributes "vertical" and either "red" or "green". With this collection of preattentive objects, a guided search for the file containing "green" and "vertical" can proceed efficiently.

EXPERIMENT 2: THE CONTENTS OF THE PREATTENTIVE OBJECT FILE— VERSION II

In Experiment 1, the "plus" and "line" conditions had the same red and green pixels in the same vertical and horizontal configuration. Nevertheless, the "plus" condition produced inefficient search while the "line" condition produced more efficient search. We argue that the critical difference has to do with the relationship between the vertical and horizontal segments. In the "plus" condition, they are preattentively parsed as a single object. In the "line" condition, they become parts of two objects. It might be objected that other accounts of these results are possible. For instance, the brown horizontal segments might somehow mask the horizontal segment of the plus. Experiment 2 tests the same hypothesis as Experiment 1 while holding the appearance of the display more constant between conditions.

Stimuli for Experiment 2 are shown in Fig. 6. In both conditions, the target is an "X" with a red bar tilted to the left and a green bar tilted to the right. In the "hard" condition, half of the distractors are "X"s with a green bar tilted left and a red bar tilted right. As in Experiment 1, we would predict that these distractors would be preattentively indistinguishable from the target. Both would be red and green and left and right. The other 50% of the distractors are green and brown plusses and should not be difficult to avoid in search. If we take the target element to be "red, tilted left", the plusses contain neither red nor left.

In the easy condition, the target is the only red and green "X", while in the "hard" condition it is not. In principle, the task could be performed as a conjunction of two colors and a shape. However, we have previously shown that searches for conjunctions of two colors are very inefficient for stimuli of this sort (Wolfe *et al.*, 1990).* Colors and sizes of the stimuli were identical to those in Experiment 1. All other methods were similar to Experiment 1. The same set of ten observers was tested in Experiments 1 and 2.

Results and discussion

Results were comparable to those of Experiment 1. The target present trials of the "hard" condition produce much less efficient search than do the "easy" condition (slopes 52.5 msec/item vs 11.5 msec/item). *Post hoc* tests (Tukey) reveal that the hard condition is significantly different from the easy condition ($P < 0.05$). Error rates were 5% in the "hard" condition and 2% in the "easy" condition. Best-fitting linear RT × set size functions for the blank trials were 552 msec + 116 msec/item for the "hard" condition and 380 msec + 59.6 msec/item for the "easy" condition. Again, these steep blank trial slopes indicate that observers adapted a very conservative quitting criterion.

Using a somewhat different set of stimuli, Experiment 2 supports the same conclusion as Experiment 1. Preattentive processing cannot reject distractor objects that contain all of the target attributes. In the hard condition, the red–right, green–left distractor is preattentively identical to the red–left, green–right target (not distractor). When such confusions are eliminated, as in the easy condition, search is much more efficient. Note that each condition has 50% "X" items and 25% red, 25% brown, and 50% green segments. The critical difference between the two conditions is the way in which the features are bundled into objects. As in Experiment 1, if we assume that the correct set size is actually the number of line segments and not the number of plusses and Xs, then the slopes in the hard condition become 26 and 58 msec/item, consistent with a serial, self-terminating search.

EXPERIMENT 3: STANDARD CONJUNCTION CONTROLS

According to the argument of this paper, the inefficient conditions of Experiments 1 and 2 are simple conjunction tasks made difficult by the combination of pairs of oriented and colored lines into single objects—plusses and "X"s. In order to test the assertion that the underlying conjunction searches are, indeed, simple and efficient, the plusses and "X"s were taken apart in Experiment 3 and observers were tested on the resulting, fairly standard, conjunction searches. Experiment 3(a) was a control for the plus condition of Experiment 1. The targets were green vertical and red horizontal line segments. On target present trials, *both* targets were presented. When present, the targets were adjacent but not overlapping. Distractors were red vertical and green horizontal segments. These, too, were presented in pairs in order to have a spatial layout similar to that in Experiment 1. Experiment 3(b) was a control for the hard condition of Experiment 2. The targets were adjacent red lines tilted left and green lines tilted right. Distractors were pairs of green lines tilted left and red lines tilted right, and pairs of green horizontal and brown vertical lines. Colors and sizes of stimuli were identical to those used in Experiments 1 and 2. Ten new observers were tested. All other methods were as described for Experiments 1 and 2.

TABLE 1. Comparison of target present slopes from hard conditions of Experiments 1 and 2 to the control conditions of Experiment 3

	Inefficient conjunction searches	Experiment 3—Control
Experiment 1 (plus)	47.2 msec/item	11.9 msec/pair
Experiment 2 (hard)	52.5 msec/item	10.1 msec/pair

Results and discussion

Slopes of the RT × set size functions for each observer were computed from the medians of RTs at each set size and are given in Table 1. In Experiments 1 and 2, each pair of line segments was combined into a single object. Thus, in order to make the slopes for Experiment 3 comparable to those given for Experiments 1 and 2, the set size is expressed as the number of *pairs* of line segments presented. This has the effect of doubling the normal slope estimates.

When the plusses and Xs of Experiments 1 and 2 are taken apart into colored line segments, standard, "guided" search for conjunctions becomes possible again. The slopes of 10–12 msec/item in Experiment 3 are much shallower than the approximately 50 msec/item slopes from Experiments 1 and 2. If the true set size is used to compute slopes in Experiment 3, the resulting slopes of 5–6 msec/item are comparable to the conjunction search slopes reported in the recent literature (Wolfe *et al.*, 1989; Treisman & Sato, 1990). Blank trial slopes are 48.5 msec/item for the control for Experiment 1 and 46.8 msec/item for the control for Experiment 2. These are relatively steep (even if divided by 2) and presumably reflect a conservative criterion for search termination in the face of these relatively jumbled displays (Chun & Wolfe, 1996). Error rates averaged 3% for both conditions.

Experiments 1 and 2 were conjunction searches. Experiment 3 supports the conclusion that there is nothing about those conjunction searches that makes them particularly difficult. Once the plusses and Xs are reduced to line segments, each with a single orientation

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*In the "easy" condition, the target is the same as in the "hard" condition. The "plus" distractor contains *red* but not *left* and the "X" distractor contains *left* but not *red*. Therefore, it should be possible to do a standard guided search for the conjunction of red and left.

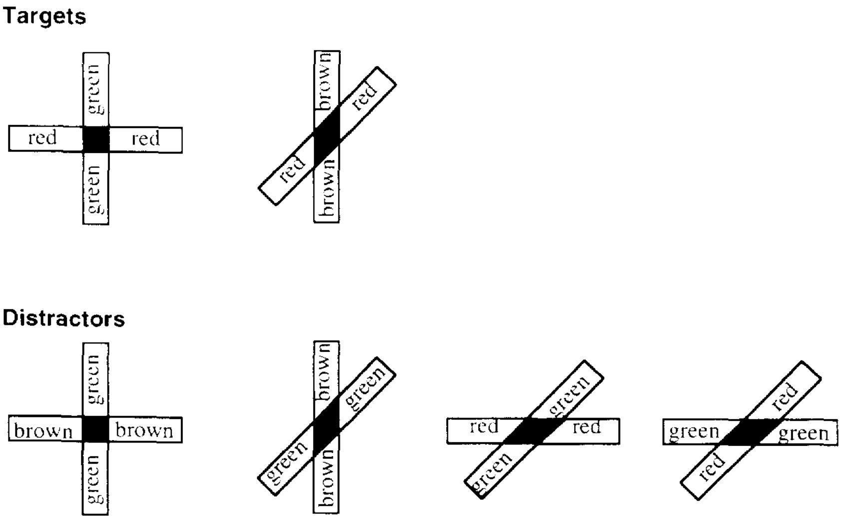


FIGURE 7. Stimuli for Experiment 4.

and color, it becomes possible to guide attention to the target conjunction of color and orientation.

EXPERIMENT 4: PREATTENTIVE OBJECTS ARE NOT COMPLETELY UNSTRUCTURED

The conception of a preattentive object file, shown in Fig. 1 is an oversimplification. It implies that nothing is known about the internal structure of the object before attention arrives. Previous data show this to be incorrect. For instance, in searches for conjunctions of two colors, we have found that search for a {red and yellow} target is very inefficient when the distractors are, say, {red and blue} and {blue and yellow} (Wolfe *et al.*, 1990). However, if the target is a whole red item with a yellow part, it can be found efficiently among whole red items with blue parts and whole blue items with yellow parts (Wolfe *et al.*, 1994). These part–whole stimuli cannot be represented preattentively as "red–yellow–part–whole". Colors must be preattentively connected to specific pieces of items. Experiment 4 illustrates this point using stimuli similar to those in Experiments 1–3. At the same time, the results provide further support for the existence of preattentive objects.

Stimuli

The stimuli for the "object" condition of Experiment 4 are shown in Fig. 7. There are two, quite different types of target item and four types of distractor. The defining feature of the targets is that each is an object having the attributes "red" and "vertical", albeit not on the same part of the object. Each distractor type contains either red or vertical but not both. Half of the distractors contain red. Half contain vertical. Target 1 and distractor 1 share the same overall shape, as do target 2 and distractor 2.

Stimuli for the "control" condition of Experiment 4 were composed of the same line segments as those in the object condition, however, the line segments were moved apart (as in Experiment 3), creating adjacent pairs of lines. In the control condition, observers searched for the red line that was next to a vertical line. In order to make the pairing of lines clear, pairs of lines were presented within a dark gray box. Boxes were presented on a lighter blue background. Thus, in the control condition, observers could search for the box containing red and vertical.

If preattentive object files were constructed as shown in Fig. 1, the object condition should support efficient search, as attention is guided to the object file containing red and vertical. The control condition should be more difficult because no single object would contain red and vertical. Ten observers were tested. In all other respects, the methods were similar to those for Experiments 1–3.

Results and discussion

Slopes for the object and control conditions are give in Table 2. Two facts are apparent. First, search in the control condition is significantly *less* efficient than in the object condition. (Tukey's *post hoc* tests, $P < 0.05$). This result supports the contention that it is easier to find two properties of one object than one property of each of two objects (Duncan, 1984).

Second, even the object condition, the easier of the two in this experiment, is not a particularly efficient search. The search for the object that contains red and vertical is not the same as a search for a red vertical object (the difference in the language required to describe the tasks may point to the underlying differences—Wolfe, 1993; Logan, 1995). This is consistent with our earlier finding that some information about the structure of items is

TABLE 2. Results of Experiment 4

	Object condition	Control condition
Target present slopes	34.0 msec/item	101.9 msec/item
Target absent slopes	93.6 msec/item	179.8 msec/item

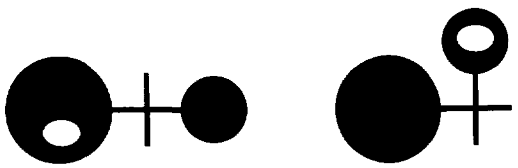
available preattentively. Experiment 4 shows that this information cannot be easily ignored.

EXPERIMENTS 1–4: GENERAL DISCUSSION

The first four experiments in this paper stress the role of objects in the preattentive representation of visual stimuli. If the visual input were not preattentively divided into candidate objects, it would be difficult to explain the differences between search tasks shown here. The experiments show that features that are part of one object are bundled together preattentively. The same features are not bundled when they do not belong to a single object. *Preattentive object file* is a useful name to give to this bundle. Experiments 1–3 support the contention that preattentive object files contain a listing of the features of an object but that the relationship of one feature to another within the file is unknown until attention is applied. Thus, a plus composed of a red vertical piece and a green horizontal piece is preattentively confused with a plus composed of a green vertical piece and a red horizontal piece. Experiment 4 complicates the issue somewhat, showing that the mechanisms of visual search are sensitive to the organization of an object. Different aspects of the search may be causing difficulties in Experiments 1 and 4. In Experiment 1, observers look for green vertical but find that it is hard to disentangle items containing green vertical pieces from items that contain both green and vertical pieces. In Experiment 4, observers are told to look for the object that contains red and vertical pieces. Perhaps the difficulty in this search is that it is harder to create a search template for red and vertical than it is to create a red vertical template (e.g. Duncan & Humphreys, 1989). Put differently, in Experiment 1, the observer knows what is being looked for but has difficulty finding it. In Experiment 4, the observer has difficulty knowing what to look for. By rejecting the simple hypothesis that preattentive object files are simple lists of features, Experiment 4 raises the issue of the structure of preattentive objects. In the second series of experiments in this paper, we turn to a specific aspect of structure—shape.

THE SHAPE OF PREATTENTIVE OBJECTS: INTRODUCTION

To review our definitions, this paper uses the term "shape" to mean some description of the shape of an object as a whole. This is distinguished from "form", the local attributes that are put together to make a shape. The choice of terms is somewhat arbitrary but the distinction is not. As discussed at the start of the paper, it is clear that a number of local attributes of form can serve as basic features in visual search. Though controversy remains, the form features probably include attributes like line termination, holes, and, perhaps, line intersections. Regardless of the final disposition of the list of form features, that list does not define the object's shape as is shown in Fig. 8.



Two disks, a hole, two terminators and an intersection.

Two disks, a hole, two terminators and an intersection.

FIGURE 8. Are these stimuli preattentively identical?

The second set of experiments in this paper asks if efficient search is possible for target objects that share *form features* with distractors but that differ in *shape*. Given that our answer is going to be that there is no evidence for the preattentive processing of shape in visual search, why is it a reasonable question to ask in the first place? A number of lines of evidence point to the possibility of preattentive processing of shape. First, given the evidence, discussed above, for object-based deployment of attention, it seems reasonable that those objects would have some shape. Second, there are a number of cases of efficient search for targets that do not seem to be differentiated from their distractors by any of the established basic features. Perhaps the most striking of these findings are the reports of efficient searches for mirror-reversed "Z"s among "Z"s and for mirror-reversed "N"s among "N"s (Wang *et al.*, 1994).* Third, Treisman *et al.* (1992) trained observers to search for items made of arbitrary arrangements of lines. After up to 16 hr of training, subjects were able to search quite efficiently for these. Finally, Treisman & DeSchepper (1993) have found long-lasting negative priming for novel and meaningless closed curves. In the standard negative priming paradigm (Tipper, 1985, 1992; Tipper & Cranston, 1985), observers are presented with two overlapping figures; letters, for example. One of these is the target, usually indicated by color. The other form is to be ignored. Thus, observers might see a red "A" overlapped by a green "B" and be asked to simply name the red letter. The critical case occurs when the ignored green letter from trial N becomes the red target letter on trial $N + 1$. In this case, observers are slightly slower to respond to the target letter. It appears that the act of ignoring the letter on trial N attaches some inhibition to that letter which remains effective on the subsequent trial.

Treisman and DeSchepper looked for and found negative priming with arbitrary closed curve targets and distractors. In this case, the task was to match the red shape with a nearby white shape while ignoring an overlapping green shape. They found that the negative priming in this case could last for 200 intervening trials and could persist when several days intervened between initial exposure and subsequent test. This is a striking

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*These searches are asymmetrical. The standard letter is difficult to find among mirror-reversed distractors. Wang *et al.* argue for some sensitivity to novelty. See also Hawley *et al.* (1994); Johnston *et al.* (1993).

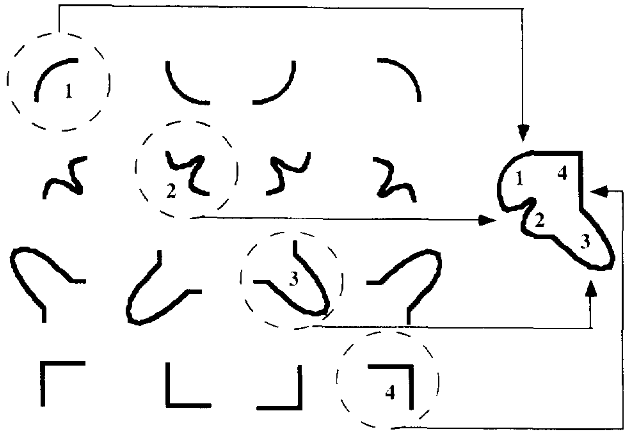

FIGURE 9. Four arbitrary pieces of curve are created. Each can used in four rotations separated by 90 deg. These can be assembled into various closed curves.

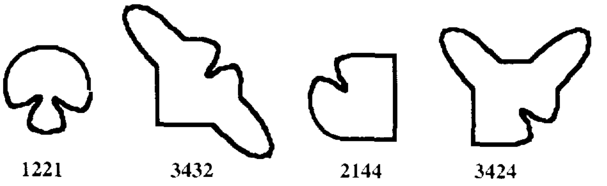

FIGURE 10. Examples of shapes that can be created from the four elements in Fig. 9.

result because, unlike negative priming with known objects like letters, this suggests that a 1 sec exposure to a novel shape is adequate to produce an internal representation that lasts for days. This is an *implicit* representation in the sense that observers show no explicit recall of the ignored items (Roediger, 1990; Schacter, 1987).

If observers can develop a long-lasting representation of one shape while attending to another, perhaps that indicates that shape is being processed preattentively. Moreover, the apparent ability of *any* arbitrary shape to produce this effect suggests that there may not be a small list of shape primitives but that many or even all shapes are "primitive shapes". The chemical senses provide what might be a useful analogy (reviewed by Bartoshuk & Beauchamp, 1994). A visual dimension like orientation is analogous to taste. There are four basic tastes (defined as the sensations produced by the taste buds of the tongue and not as a synonym for "flavor"). These are sweet, sour, salt, and bitter. All other taste sensations are mixtures of those four. In the same way, preattentive orientation processing appears to be categorical with four basic categories: steep, shallow, left and right (Wolfe *et al.*, 1992a). Perhaps shape is like olfaction, where a host of specific receptors respond to a host of specific odor molecules. No small set of basic smells can account for the set of all smell stimuli. "Mint" just isn't "floral" + "piney" or any other combination. It is "mint". Given the negative priming evidence, perhaps each new shape becomes its own preattentive primitive. Based on these lines of evidence, it seemed reasonable to look for evidence for preattentive processing of overall shape.

EXPERIMENT 5: SEARCH AMONG ITEMS WITH THE SAME FORM FEATURES BUT DIFFERENT OVERALL SHAPES

We conducted a series of pilot experiments using the shapes from Treisman and DeSchepper's work.* Some of the shapes supported efficient search when used as targets. Most others did not. Thus, we could reject the hypothesis that *every* distinctive shape can behave like a basic feature and support efficient visual search. It seems likely that the items that supported efficient search had some distinctive form features. Since our interest here is in the preattentive processing of the overall shape of an item, it is necessary to control for the effects of form. This would be easier if there were some consensus about the set of preattentive form primitives. If we knew the set of form features, we could use stimuli composed of different arrangements of form features A, B, and C. These different arrangements would yield different overall shapes in items with the same component form features.

Since there is no consensus about the list of form features, the stimuli for Experiment 5 attempted to achieve the same goal of different shape with similar forms with a slightly different strategy. The method for generating stimuli is illustrated in Figs 9 and 10.

Four arbitrary pieces of curve were generated. These are designated as pieces 1,2, 3 and 4 in Fig. 9. Each piece can be rotated by 90, 180, and 270 deg. If one piece is taken from each of the four rotations, these four pieces can be assembled to make a single, closed curve figure. In Fig. 9, this is shown for piece 1 at 0 deg, 2 at 90 deg, 3 at 180 deg, and 4 at 270 deg. This shape can be denoted as shape "1234". Figure 10 shows four other shapes made in the same way. No claims are being made about the status of the pieces. They are not intended to be "features" nor orthogonal to each other in any feature space. They are merely different from one another. When they are combined in the manner illustrated, they can generate a large collection of distinctive shapes that share most, if not all, form features. The pieces are drawn so that they meet in a straight line. They do not form inflection points when joined together. When one of these shapes is the target and others are distractors, observers must search for the target on the basis of shape. There is, in principle, no preattentive form feature information that can be used to distinguish targets from distractors.

Methods

In Experiment 5, the target item was shape 1234 as shown in Fig. 9. Distractors were drawn at random from shapes like those in Fig. 10. Each distractor shape was constrained to contain no more than three of the four pieces. Thus, at least one piece needed to be repeated in each shape. This ensured that simple rotations of the target (e.g. 4123) could not appear in the distractor set.

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*We thank Anne Treisman for providing us with these stimuli.

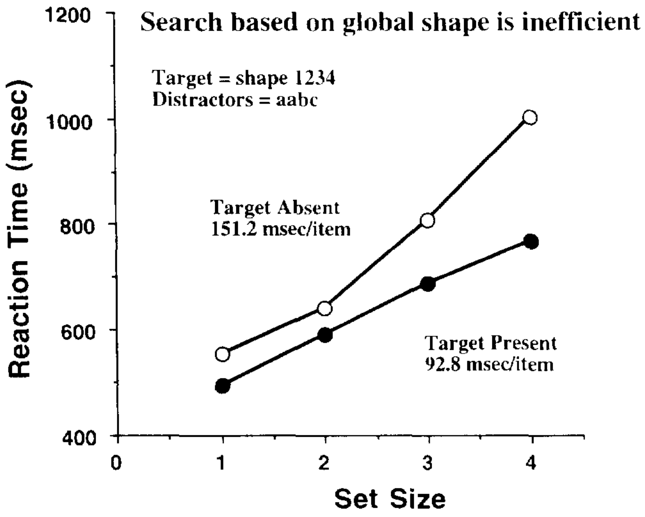

FIGURE 11. Results for Experiment 8. Search for target defined only by shape is very inefficient.

All pieces could appear in the search display. They simply could not all appear in the same distractor. Shapes had different dimensions depending on their component pieces. The maximum size was 3.1 by 3.1 deg. To minimize the effects of crowding and decline in acuity with peripheral viewing, set sizes were restricted to 1, 2, 3, or 4 items and all items were presented within 7.5 deg of fixation. Items were randomly placed in cells of a 3 × 3 array. Ten new observers were tested. They performed 50 practice and 300 experimental trials. In all other respects methods were similar to those of previous experiments.

Results and discussion

The averages of the median RTs for each observer are shown in Fig. 11 for target present and target absent trials. Average error rates were 4.6% for set size 1, 7.2% for set size 2, 11.0% for set size 3, and 10.9% for set size 4.

It is immediately clear that this search is very inefficient. Standard estimates of "serial" search suppose that items can be searched at a rate of one item every 40 or 50 msec. The slopes of the RT × set size functions for Experiment 5 are consistent with serial processing at rates 3 to 4 times *slower* than that. If we assume that attention can be deployed at a rate of one item every 50 msec, this suggests that these stimuli required 100+ msec of additional processing once attention arrived. This is reminiscent of the "plus" stimuli of Experiment 1, where the act of binding two colors to two orientations seemed to take an unusually long time. In this experiment, it seems that it takes a long time to bind together the form elements (whatever they may be) into a shape.

Of course, this is only a single finding and a negative one at that. The next few experiments test the generality of the result.

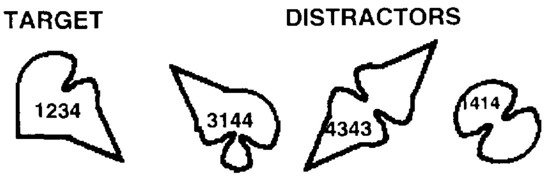

FIGURE 12. Stimuli for Experiment 6(a).

FIGURE 13. Target for Experiment 6(b).

EXPERIMENT 6: TWO VARIATIONS

In an effort to make the search task easier, two conditions were created in which the target had a unique piece. In Experiment 6(a), the target was shape 1234 as in Experiment 5 (see Fig. 12). The distractors were constrained to contain only pieces 1, 2, and 3 so piece 4 (the "right angle") was unique to the target. In Experiment 6(b), a new piece was added to the target. As shown in Fig. 13, this was a curve with an adjacent circle. The distractors were composed of pieces 1, 2, 3 and 4. In Experiment 6(b), therefore, the target was the only item with the fifth piece and the only item that was divided into two pieces. Methods were otherwise similar to Experiment 5. The ten observers from Experiment 5 were also run in Experiment 6.

Results and discussion

Slopes and intercepts of the RT × set size functions were computed based on median RTs for each observer at each set size. In Experiment 6(a), the slopes were 49 msec/item for target present and 91 msec/item for target absent trials. In Experiment 6(b), the slopes were 27 msec/item for target present and 43 msec/item for target absent. Average error rates were 4.4% for set size 1, 5.8% for set size 2, 5.8% for set size 3, and 4.9% for set size 4. Experiment 6(a) and 6(b) did produce more efficient search and somewhat lower error rates than did Experiment 5. However, there was no evidence for preattentive processing of the shape of these targets. Recall that standard "serial" searches yield slopes of 20–30 msec/item on target present trials and about twice that for target absent trials. Experiment 6(a) demonstrates that the "right angle" is not a basic form feature in this context. This merely reinforces the point, made earlier, that the pieces used in experiments 5 and 6 were not chosen as representatives of a principled set of form features. They were picked atheoretically, purely for their ability to be put together to form different shapes with the same underlying form features, whatever those features might be. The results of Experiment 6(b) are slightly more surprising, since one might think that the addition

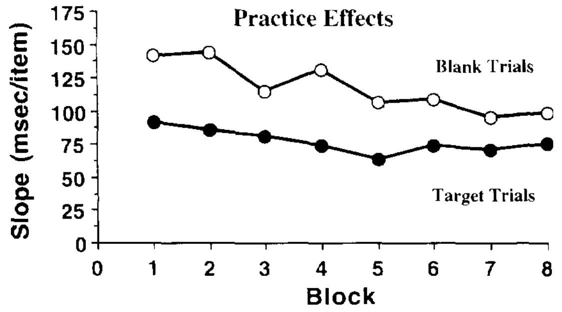

FIGURE 14. Two thousand four hundred trials of practice with the stimuli used in Experiment 5 fail to yield efficient search.

of a second part to the target would be a change in topology that might be detected preattentively (Chen, 1982, 1990; Zhou *et al.*, 1992). In somewhat different experiments, preattentive sensitivity to part–whole relationships was greater when the whole surrounded the part (Wolfe *et al.*, 1994). Some evidence for preattentive processing of parts is given in Experiment 10 below. For the present purposes, the conclusion of these two experiments is negative. There is no evidence for preattentive processing of shape using these stimuli.

EXPERIMENT 7: PRACTICE EFFECTS

The stimuli used in these experiments are relatively complex (when compared, say, to colored bars). Perhaps observers simply need more practice with this type of search. There is evidence for efficient search for relatively complex shapes when observers have extended experience (Shiffrin & Schneider, 1977; Treisman *et al.*, 1992). Accordingly, Experiment 5 was repeated with a new group of ten observers. Each observer was tested for 2400 trials divided into eight blocks of 300 trials. These were spread over 4 days. Average slopes of the RT × set size function for each block are shown in Fig. 14.

While there is some improvement with practice, 2400 trials did not produce anything close to an efficient, "parallel" search. In some perceptual learning tasks, learning only appears after several hours (perhaps after a good night's sleep—Karni & Sagi, 1993; Karni *et al.*, 1994). However, the blocks in Experiment 7 were spread over 4 days, providing plenty of opportunity for any such consolidation.

Given that efficient search is possible for letters (Schneider & Shiffrin, 1977; Schneider, 1993; Shiffrin & Schneider, 1977) and for meaningless figures with sufficient practice (Treisman *et al.*, 1992), why didn't practice produce efficient search? One possibility is that more practice is required. Alternatively, the design of these stimuli may have made them unlearnable. Unlike letters and unlike the arbitrary shapes of Treisman *et al.* (1992), the shapes used in these experiments were designed to have no distinctive form features. We may not know what the form features are in the case of letters or of the arbitrary shapes in Treisman *et al.* (1992) but it is possible that learning to search for these stimuli involves the implicit discovery of a usable form feature. Since the stimuli used here deliberately make such features difficult or impossible to find, it is not surprising that practice fails to make perfect.

The results of Wang *et al.* (1994) are the sternest test of our argument that the published instances of "parallel" search for shape rely on observers making use of some feature other than shape. As noted earlier, their data show efficient searches for mirror-reversed "Z"s among "Z"s and for mirror-reversed "N"s among "N"s. It is hard to see that any local form feature would account for this ability. It is possible that a preattentive sensitivity to spatial phase might be utilized. It may be that there is some parallel processing of a limited number of overlearned stimuli. There is a difficulty in interpreting results of experiments where a target can be found among homogeneous distractors. *Something* must distinguish targets from distractors in these searches, otherwise the targets and distractors would be indiscriminable. In the absence of a clear idea about the identity of that something, it is difficult to draw conclusions about the basis of efficient search.

EXPERIMENT 8: HOW DISCRIMINABLE ARE THESE SHAPES?

Perhaps search is difficult in Experiments 5–7 because the target and distractors are too similar to one another. At the preattentive level of visual processing, this is exactly what we propose is occurring. The targets and distractors are preattentively indistinguishable and search must proceed in a serial, self-terminating manner without benefit of guidance from preattentive processes. A less interesting possibility is that subjects just can't tell one item from another. The items might be too similar when examined by the visual system as a whole. Looking at Figs 10 and 12, the items appear to be quickly discriminable when attended. Nevertheless, Experiment 8 was performed to determine if the target could be rapidly distinguished from the distractors.

In this experiment, one item was presented at fixation on each trial. On half of the trials, this was the target item from Experiment 5 "1234" and on the other half it was one of the distractors from Experiment 5. The item was presented for 45 msec, roughly the duration of one attentional "fixation". Presentation was followed by a 30 msec blank ISI and then by a mask composed of fragments of the items. Subjects simply identified each item as either target or distractor. Eight subjects were tested for 25 practice and 100 experimental trials.

All subjects had error rates under 6%, clearly showing that the items were sufficiently different to allow discrimination of target from distractors within 75 msec.

EXPERIMENT 9: SEARCHING FOR CHICKENS AMONG CHICKEN PARTS

In light of results like those of Wang *et al.* (1994), perhaps our observers failed to search efficiently for the shapes in Experiments 5–7 because the objects were

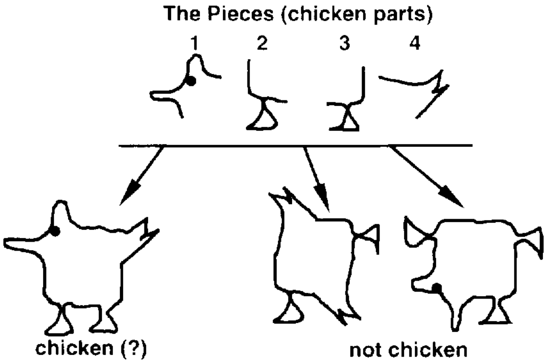

FIGURE 15. Stimuli for Experiment 9.

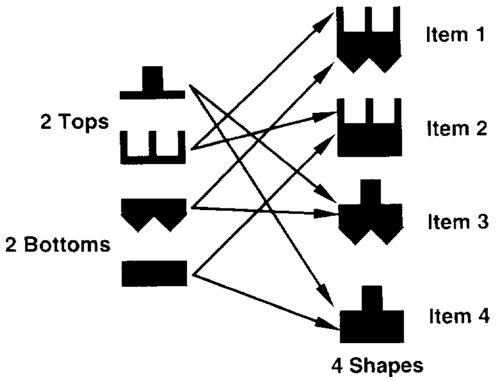

FIGURE 16. Stimuli for Experiment 10.

unfamiliar. Though the different shapes appear to be distinctive, they might be like so many distinctively shaped rocks—different and yet similar. In Experiment 9, observers again searched for a target defined by shape, but in this experiment the targets and distractors differed in meaning as well as shape.

Methods and stimuli

The design of stimuli for Experiment 9 is shown in Fig. 15. As in Experiments 5–8, there are four "pieces" that can be rotated and combined to create a large number of shapes. In this case, however, shape 1234 is recognizable as a bird of some sort.* Other combinations of pieces do not look like birds.

The experiment was a repeat of Experiment 5 with new stimuli. There were two conditions. In the "chicken" condition, observers searched for shape 1234 among items constrained to have no more than three of the four pieces. There have been claims that unusual or novel items "pop-out" of arrays of familiar items (Hawley *et al.*, 1994; Johnston *et al.*, 1993; Wang *et al.*, 1994). Accordingly, a "not chicken" condition was run where the *distractors* were constrained to be "chickens"—shape 1234 or its simple rotations. The target was item 1212, the item that was *not* a chicken. Ten new observers were tested. The sizes of stimuli were comparable to those used in Experiments 5–8. The set sizes were again restricted to 1, 2, 3 and 4. All other aspects of experimental design followed Experiment 5.

Results and discussion

Average slopes were computed from the median RTs for each observer. Search is very inefficient. Target trial slopes were 86.5 msec/item for the "chicken" condition and 160 msec/item for the "not chicken" condition. Blank trials slopes were 141 msec/item for the chicken condition and 208 msec/item for the not chicken condition. Average error rates were 3.2% for set size 1, 4.2% for set size 2, 4.4% for set size 3, and 8.4% for set size 4. As in Experiments 5–7, there is no evidence for preattentive processing of shape. It is always risky to draw conclusions from negative results. Perhaps a better bird or some other recognizable object would have produced efficient search. It cannot be complained that these stimuli are particularly hard to discriminate one from the other. It took about 500 msec for an average subject to identify a "chicken" when it was the only item on the screen (set size 1). This is comparable to the times for target identification in simple feature or conjunction searches in our lab (see Friedman-Hill & Wolfe, 1995 for example). Nevertheless, the stimuli used in Experiments 5–9 are relatively complex. Experiment 10 reproduces the inefficient search for shape using simpler shapes.

EXPERIMENT 10: SIMPLE SHAPES

Methods and stimuli

The stimuli for Experiment 10 are shown in Fig. 16. Two "tops" were combined with two "bottoms" to yield a total of just four possible shapes. As in the previous experiments, no claims are made about the featural status of the pieces. They are merely intended to be different from each other and to be relatively simple.

There were three conditions. For all conditions, item 1 was the target. It has the pointy bottom and "crown" top. In the "shape" condition, the distractors were items 2 and 3. Item 2 has the crown top and item 3 has the pointy bottom. Thus, no form feature defines the stimulus. Search could be based on the overall shape since items 1, 2, and 3 look quite different. This condition could be described as a conjunction search–search for the item that has a crown and points among items with either crowns or points but not both. It is the conjunction of properties of two parts. Similar part–part conjunction searches have been shown to be very inefficient (Bilsky & Wolfe, 1995; Wolfe *et al.*, 1994).

Two feature searches were used as control conditions. In the crown condition, observers looked for item 1 among items 3 and 4, making the target the only item with the crown (perhaps a spatial frequency feature). In the points condition, observers looked for item 1 among items 2 and 4 making the target the only item with the points (perhaps an orientation feature). Set sizes were 3, 6

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*The resemblance to any real bird is, admittedly, a bit weak. This reflects (a) a lack of artisitic ability; and (b) the deplorable lack of interchangable quarters in real birds.

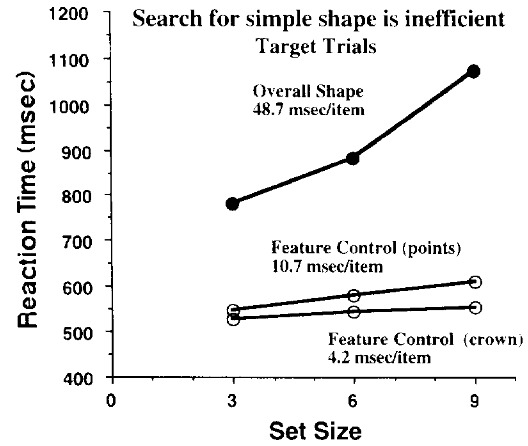

FIGURE 17. Target present data for Experiment 12.

and 9. Stimuli were 2.5 by 2.0 deg. Ten observers were tested. Other methods resembled those of previous experiments.

Results and discussion

Averages of the median RTs for the target present trials for each subject are plotted in Fig. 17. Even with these simpler stimuli, observers were unable to search efficiently for the overall shape of the target.

Blank trial slopes were 130 msec/item for the shape condition and 29 and 40 msec/item for the points and crown feature control conditions. The ratios of target absent to target present slopes are greater than the usual 2.0, suggesting that observers adopted a conservative quitting criterion when they did not find the target (Chun & Wolfe, 1996). Average error rates were approximately 3% across conditions and set sizes.

The results of Experiment 10 bolster the general argument that visual search cannot make use of a preattentive representation of shape. In the previous experiments, even targets with a unique piece could not be found efficiently. In Experiment 10, however, the individual pieces do have properties that permit efficient search. A target with a unique part was easy to find. Conjunctions of those parts were hard to find even though the conjunction creates a shape that distinguishes the target item from the distractors. As in Experiments 5–9, there is no evidence the preattentive processes can make use of that information.

EXPERIMENT 11: DEFINING SHAPE BY MINIMA OF CURVATURE

As has been noted several times above, the pieces that were used in Experiments 5–10 as components of shape were generated atheoretically. These experiments do seem to reject the hypothesis that shape, in general, is available preattentively. However, it is still possible to entertain the hypothesis that *some* aspects of shape can be used to guide visual search. Hoffman & Richards (1984) have proposed that objects get cut into parts at points of minimum curvature. In Experiment 11, we examined the sensitivity of the preattentive stage of visual processing to this division.

Stimuli and methods

Figure 18 shows how the stimuli for Experiment 11 were created. The core of the figure was a set of three abutting circles. These created four cusps or inflections, any or all of which could be eliminated to create oblong stimuli with 0, 1, 2, 3, or 4 inflections. In this experiment, only 0, 1, and 2-inflection stimuli were used. In each of six conditions, one stimulus was the target and one was the distractor. The distractors were homogeneous. Stimuli could be vertical or horizontal. Set sizes were 2, 4 and 6. Ten subjects were tested. Other aspects of the experiment were similar to those in previous experiments.

It is easiest to describe the stimuli for each of the six conditions, together with the results for that condition. The stimuli and the average target present and target absent slopes are shown in Fig. 19.

Results

Condition 1. Here the target has an inflection and the distractor does not. Search is quite efficient. The blank trials are actually somewhat more efficient than the target trials. Thus, the local feature formed by the inflection does seems to be preattentively available.

Condition 2. In this case, the distractors all have one inflection while the target does not. This search is much less efficient, producing slopes characteristic of searches thought to be serial, self-terminating. This is a classic search asymmetry (Treisman & Souther, 1985) where the presence of a feature is found more efficiently than its absence.

Condition 3. The target in this condition has two inflections. The distractors have only one each. The

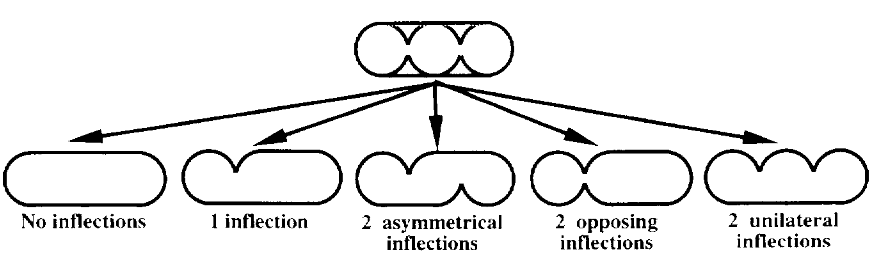

FIGURE 18. Creating stimuli for Experiment 11.

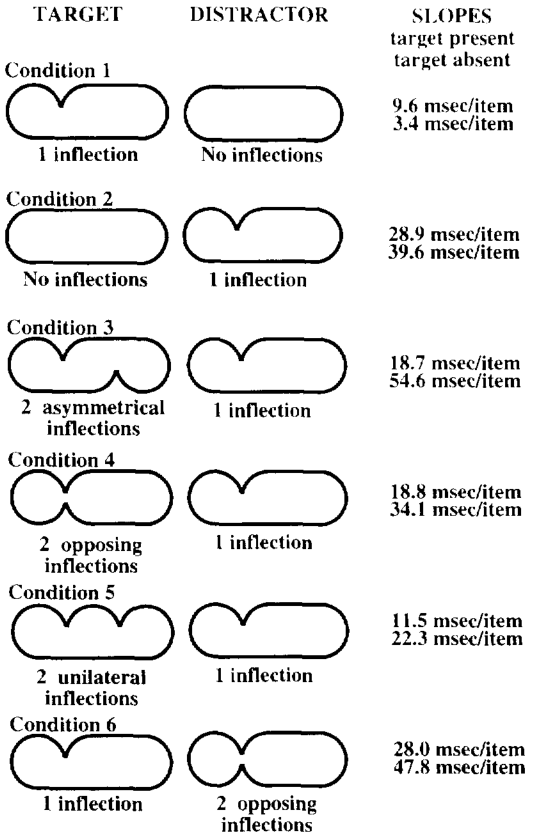

FIGURE 19. Stimuli and results for the six conditions of Experiment 11.

shapes of the two types of items are quite different but, because the target's inflections are asymmetrical, Hoffman and Richards' model would argue that the target, like the distractor, has only one part. Search is quite inefficient. Slopes are comparable to "serial" search tasks. Apparently, the number of inflections is not a particularly good cue for visual search.

Condition 4. Here, the two inflections on the target are opposite to one another. Introspection and Hoffman and Richards would divide this target into two parts. Search for this two-part item among distractors with a single inflection is not very efficient. Indeed, target trial slopes are virtually identical to those for Condition 3. However, there is some evidence that this search for a two-part object among one-part distractors is somewhat more efficient than the search in Condition 3. Blank trial slopes are significantly shallower ($t(9) = 3.2$, $P < 0.02$) and mean RTs are about 50 msec faster in Condition 4 ($F(1,9) = 6.42$, $P < 0.05$).

Condition 5. In Condition 5, the two inflections on the target item are on the same side. Search is significantly more efficient than Condition 3 but not significantly more efficient than Condition 4 (Tukey's HSD tests). Though Hoffman and Richards' (1984) theory would make this a bumpy item with a single part, it could be that the single inflections are enough to induce a weak division into parts. If that were the case, Condition 5 could be considered to be a search for target weakly divided into three parts among distractors weakly divided into two parts.

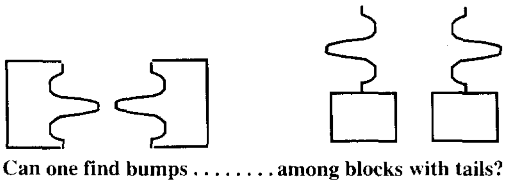

FIGURE 20. Both types of objects are closed figures with a squiggle.

Condition 6. Finally, Condition 6 shows a search asymmetry with Condition 4. This bolsters the argument that the second inflection in the target of Condition 4 adds something that is available, albeit weakly. When observers search for the absence of that something, search is less efficient.

Discussion

As in the Experiments 5–10, substantial differences in shape did not support efficient search in Experiment 11. However, Experiment 11 serves a cautionary role as did Experiment 4. While preattentive objects may be shapeless, they are not entirely without structure. In Experiment 11 we see that search appears to be somewhat more efficient when the target and distractors differ in their part structure. This evidence for the preattentive processing of part structure is suggestive and deserves further research. It is consistent with results showing preattentive sensitivity to the hierarchy of parts and wholes (Bilsky & Wolfe, 1995; Wolfe *et al.*, 1994; see also Farah, 1992; Kimchi, 1992; Paquet, 1992; Robertson & Lamb, 1991). Moreover, it makes the broader point that preattentive representations are quite sophisticated—a topic that we will return to in the General Discussion.

EXPERIMENT 12: PREATTENTIVE OBJECTS ARE THE SUM OF THEIR PARTS

If, as this paper has maintained, preattentive object files are loose collections of the attributes of the object, then search for a target among distractors should be inefficient whenever the target and distractors have the same preattentive attributes. This should be true, even if the items look very different from each other. The final experiment illustrates this point with the stimuli shown in Fig. 20.

The items on the left of Fig. 20 are composed of a "closed curve" and a "squiggle" (Curvature is a basic feature see Fahle, 1991; Wolfe *et al.*, 1992b). The items on the right also have those two attributes. The items on the right may also have the attribute of line termination (Julesz & Bergen, 1983). In addition, they are longer than the items on the left and may be composed of two parts. The two types of shape, call them "bump" and "tail" stimuli, seem very different. However, the account developed in this paper would predict that it would be difficult to find a bump among tails because all of the

TABLE 3. Results of Experiment 12

	Bump	Tail
Target present	18.9 msec/item	14.4 msec/item
Target absent	74.5 msec/item	32.5 msec/item

attributes of the bump stimuli are also attributes of the tail stimuli. Since it is difficult to search for the absence of a feature, the absence of line termination in the bump stimuli will not aid search for those stimuli. Search for a tail target among bump distractors should be more efficient because of the presence of a terminator.

Two conditions were run. In one, observers searched for bumps among tails and in the other they searched for tails among bumps. Bump stimuli were 2.2 by 2.0 deg. Tail stimuli were 3.2 by 1.5 deg. Set sizes were 3, 6, and 9. Ten observers were tested. All other aspects of the experiment were similar to previous experiments.

Median RTs were computed for each observer and the average of those medians is given in Table 3. As predicted, the search for bump stimuli among tail distractors is inefficient, with slopes comparable to standard serial search. There is a search asymmetry. Target absent trial slopes are significantly shallower in searches for the tail target than in searches for the bump target ($t(9) = 6.1$, $P < 0.001$) Target present trial slopes are marginally significantly different ($t(9) = 2.1$, $P = 0.064$) and the search for the tail stimuli is significantly faster than the search for the bump target ($F(1,9) = 67.4$, $P < 0.0001$).

There are at least two reasons why search for bumps among tails might be inefficient. The account given by this paper is that they form similar preattentive object files. The less interesting alternative is that the squiggle or the line termination are simply not detected preattentively. The latter account is ruled out by control experiments. In one, the target was the bump stimulus and the distractors were rectangular blocks of the same extent. This is a highly efficient search (slopes around 0 msec/item) showing that the squiggle can act as a feature. In the second pilot experiment, the target was a block with a straight line terminator instead of the squiggle tail. Distractors were blocks without a straight line terminator. Again, search was very efficient, replicating the standard result that line termination can act as a feature (Treisman & Gormican, 1988). If the terminator is a feature, why wasn't the search for the tail stimulus among the bumps more efficient? Looking at Fig. 20, one possibility is that the bump is, in fact, a blunt terminator. It might not be as good a terminator as a line ending but it might be sufficiently like a terminator to make search rather inefficient in the tail among bump condition of this experiment. The bottom line for this experiment is that a target of one shape can be very difficult to find among distractors of another, very different shape, if those shapes are preattentively represented by similar collections of basic features and attributes.

GENERAL DISCUSSION

The central argument of this paper is that, prior to the arrival of attention, objects are represented as shapeless collections of attributes. In the first four experiments, observers searched for conjunctions of color and orientation embedded in various objects. When observers had to search through compound items that all had red, green, vertical, and horizontal attributes, search was very inefficient. When we broke up the compound objects into objects each having a single color and orientation, search became much more efficient. These experiments support the increasingly popular view that attention operates over objects rather than over simple spatial location. Borrowing from the terminology of Kahneman & Treisman (1984), it is useful to think about these shapeless collections of attributes as preattentive "object files". The evidence of Experiments 1–3 indicates that preattentive object files consist of a collection of the attributes of the object and that a role of attention is to bring to the object the resources required to determine how those attributes relate to each other. Experiment 4 suggests that the structure of the item is not entirely irrelevant. Some aspects of structure are available preattentively.

Experiments 5–11 illustrate that the overall shape of an object is not available preattentively. In experiment after experiment, targets could not be found efficiently, even when the distractors had a very different overall shape. As in Experiment 4, the results of Experiment 11 seem to show that the structure of an item can make a difference. Specifically, relatively efficient search may be possible for a target with two parts if the distractors have only one part apiece.

There is evidence from a variety of other labs for some limited processing of shape. For instance, Donnelly *et al.* (1991) have a series of experiments with items composed of four "L" features. The overall configuration of these items determines the efficiency of search. Thus, when the Ls form squares as distractor items, it is easy to find the target that has one "L" corner pointing the wrong direction. This is, perhaps, a version of a "closure" feature (Elder & Zucker, 1993; Williams & Julesz, 1989). A similar principle may lie behind Pomerantz and Pristach's (1989) finding that adding the same element to targets and distractors can actually improve search. For instance, a search for "(" among ")" can be reasonably efficient (Wolfe *et al.*, 1992b), but it can be made more efficient by adding ")" to both items, creating a search for "()" among "))". Results of this sort remind us not be too dogmatic about any assertion that there is no preattentive processing of overall shape. It seems more accurate to say that any preattentive processing of shape is quite limited.

If we define the preattentive visual representation in operational terms as the visual representation that is searched when we perform a visual search task, then we can see that our conception of preattentive vision has evolved considerably from Treisman's original proposal of a preattentive world populated by free-floating instances of a limited number of basic features (Treisman & Gelade, 1980). Parallel processes parse the world into objects. This set of preattentive objects may not be the same set as the set of perceived objects but some division is made in parallel. The objects can be thought of as *preattentive object files* that act as holders for a collection of attributes that inform subsequent processing. These attributes include a limited set of basic features (perhaps a dozen or so—see Wolfe, 1994, 1996a for reviews of the evidence on basic features). These features have been quite heavily processed before they become part of the preattentive representation. To use orientation as an example, the representation of orientation in preattentive vision seems to be categorical with orientations divided into groups corresponding to "steep", "shallow", "left" and "right" (Wolfe *et al.*, 1992a). Moreover, observers can search for orientation defined by a wide variety of surface properties. An oriented color patch will support search as will orientation defined by texture, motion, depth, and so on (Bravo & Blake, 1990; Gurnsey *et al.*, 1992; Cavanagh *et al.*, 1990).

Not only have basic features received substantial processing by the time they reach the preattentive visual representation, there are other attributes that can only exist as attributes of an object. As noted above, some information about the part–whole structure of objects is available preattentively (Bilsky & Wolfe, 1995; Wolfe *et al.*, 1994). The creation of preattentive objects actually requires the loss of some low-level feature information. For instance, Rensink & Enns (1995) have shown that size information that is readily perceived preattentively, can be lost in the creation of objects. In short, considerable processing is required to create the preattentive visual representation.

That said, we are not advocating some sort of late selection model in which all the work is done by preattentive processes. The results presented here show just how incomplete the preattentive representation is and how much work is left for attentive processes to complete. While nearly 20 years of research have required many modifications of Treisman's original Feature Integration account, the core insight seems correct. Preattentive vision can represent many attributes of a visual stimulus but attention is required to appreciate the relationships between attributes. Prior to the arrival of attention we may know that an item has curves, intersections, and line terminators but we do not know the shape of that item until attention has bound these form features together.

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