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The Role of Categorization in Visual Search for Orientation

Jeremy M. Wolfe
Brigham & Women's Hospital and Harvard Medical School

Stacia R. Friedman-Hill
Brigham & Women's Hospital

Marion I. Stewart
University of California, San Diego

Kathleen M. O'Connell
University of California, Berkeley

Visual search for 1 target orientation is fast and virtually independent of set size if all of the distractors are of a single, different orientation. However, in the presence of distractors of several orientations, search can become inefficient and strongly dependent on set size (Exp. 1). Search can be inefficient even if only 2 distractor orientations are used and even if those orientations are quite remote from the target orientation (e.g. 20° or even 40° away, Exp. 2). Search for 1 orientation among heterogeneous distractor orientations becomes more efficient if the target orientation is the only item possessing a categorical attribute such as *steep*, *shallow* (Exp. 3), *tilted left* or *tilted right* (Exp. 4), or simply *tilted* (Exps. 5 and 6). Orientation categories appear to be 1 of several strategies used in visual search for orientation. These serve as a compromise between the limits on parallel visual processing and the demands of a complex visual world.

The visual processing required to search for a target item in a field of distracting items can be divided into two major stages. At the first stage, a limited set of basic visual features can apparently be processed in parallel across the entire visual field (Julesz, 1984; Treisman & Gormican, 1988). At the second stage, more complex processing is possible, but at any moment in time, it is restricted to a limited region of the visual field (Neisser, 1967; Treisman & Gelade, 1980). The deployment of this limited processing capacity is under attentional control. Searches requiring the movement of attention from location to location appear to be serial and self-terminating (but see Townsend, 1971,1976,1990). Movements of attention can be guided by information from the parallel, first stage of processing (guided search model: Cave & Wolfe, 1990; Wolfe, Cave, & Franzel, 1989; see also Egeth, Virzi, & Garbart, 1984; Hoffman, 1978, 1979; Treisman & Sato, 1990). "Guided" searches blur the distinction between "serial" and "parallel" searches because they have both serial and parallel components. Initial parallel processes restrict subsequent serial (or, at least, limited-capacity) processes to a subset of the available stimuli.

Parallel guidance of subsequent, attentional processing has two aspects: bottom-up and top-down. In bottom-up guidance, attention is attracted to areas of unusual variation in one feature type. Thus, a single red item among green items or a single moving item among stationary items will attract attention. In fact, a unique item may attract attention even if the subject would prefer to ignore the item (Jonides, 1981; Pashler, 1988; Yantis & Johnson, 1990). In Treisman's (1986) terms, bottom-up guidance produces *pop-out*. In Julesz's terms, these unusual items form steep *texton gradients* (Bergen & Julesz, 1983; Julesz & Bergen, 1983).

In some cases, parallel guidance of attention remains possible even in the absence of bottom-up guidance. This is accomplished by top-down guidance. The observer, in some fashion, orders the parallel stage to look for a particular feature or features. For example, it is possible to perform a parallel search for a target item of one color among a set of distractors each of a unique color (Duncan, 1989; Wolfe et al., 1990). Here, in the absence of top-down information about target identity, the search task would be impossible. As a second example, consider the search for a conjunction of color and orientation. The target is a red vertical line. Half the distractors are red horizontal; the other half are green vertical. Here there is no bottom-up guidance because half the items are red and half are green; half are vertical and half are horizontal. Nevertheless, we have shown that it is possible to guide attention to the red and vertical items, thus making the search for the red–vertical conjunction quite efficient (Cave & Wolfe, 1990, Wolfe, Cave, & Franzel, 1989).[1] Indeed, it has become

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Correspondence concerning this article should be addressed to Jeremy M. Wolfe, Center for Clinical Cataract Research, 221 Longwood Avenue, Boston, MA 02115.

[1] We will use the term *efficient* to avoid having to declare specific searches to be either serial or parallel. As noted in our opening paragraph, many searches do not treat all items as equal. Attention is attracted to some items and away from others in a systematic fashion. When all items are equally attractive to attention, search seems to proceed at a rate of 40–60 ms/item. If parallel processing can restrict attention to half of the items, the search will appear to proceed at a rate of 20–30 ms/item yielding slopes of 10–15 ms/item on target trials. This is more efficient than an unguided search, but it is not parallel. The greater the ability of the parallel front end of the system to restrict attention, the more efficient the search. In the case of guided searches that combine parallel and serial processing, the interpretation of blank trial slopes is problematical. In a serial self-terminating search, it is clear that subjects should search through all

clear in the last few years that searches for conjunctions of two features are often far more efficient than predicted by any model requiring serial, self-terminating search (e.g. Dehaene, 1989; Egeth et al., 1984; Nakayama & Silverman, 1986; Quinlan & Humphreys, 1987; Treisman & Sato, 1990).

Most of the evidence for parallel processing of basic features comes from situations where distractors are homogeneous and bottom-up guidance can be used. Indeed, when distractors are not homogeneous, evidence for parallel search or even for parallel guidance of search may become weak or nonexistent (D'Zmura & Lennie, 1988; Moraglia, 1989; Treisman, 1988). This is puzzling. Parallel processing is assumed to be a useful first step in real-world visual processing. If it breaks down in the face of background inhomogeneity, it is hard to see how it can be of much help in our distinctly inhomogeneous visual world. If we do not have an effective parallel stage, it is difficult to understand how even fairly simple visual tasks could be accomplished in a reasonable amount of time.

In this article, we examine this conundrum for a single basic feature: orientation. There is wide agreement that orientation is one of the short list of basic features that are processed at the first, parallel stage. Certainly, a single target of one orientation "pops out" of a homogeneous set of distractors of another orientation (Sagi & Julesz, 1985; Treisman & Gormican, 1988). Moraglia (1989) has shown that there is at least one case in which parallel search for one orientation is possible among a heterogeneous set of distractor orientations. If the distractors are arranged in an orderly circular pattern with all orientations perpendicular to the radius, a stimulus that is "out of order" (e.g., vertical on the vertical meridian) can be found in parallel. However, if the same distractors are placed randomly, Moraglia found that search was serial.

The inability to find the target in a disordered array is our point of departure. Clearly, it must be possible to use orientation information to guide visual search in an inhomogeneous world. Apparently, there are limits on the use of orientation information that make it impossible to search efficiently for a vertical target among the ten randomly placed distractor orientations used by Moraglia. The visual system seems to use several strategies to overcome these limits. The main purpose of this article is to demonstrate that orientation categorization is one of those strategies. That is, orientations can be categorized as *steep* or *shallow*, *tilted left* or *tilted right*, or simply *tilted*, and categorical information can be used in visual search. Duncan and Humphreys (1989) have shown that search becomes less efficient as distractor heterogeneity increases. Categorization may serve a useful role in visual search, acting to reduce the effective distractor heterogeneity by grouping a variety of orientations under a single label.

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items on blank trials. In a guided search, it is not clear when subjects should terminate an unsuccessful search. It seems likely that this is a form of signal detection task. Subjects terminate search when they are reasonably sure that they have not missed a target item. We discuss this point elsewhere (e.g., Cave & Wolfe, 1990; Wolfe & Cave, 1989).

We present two groups of experiments. The first two experiments confirm that search for one orientation can be strikingly inefficient, even for quite simple sets of distractor orientations. The remaining experiments (Experiments 3–6) show that categorical information can aid in visual search.

Experiment 1: The Basic Phenomena

In the first experiment, we have replicated the findings of parallel search for one orientation among homogeneous distractors and serial search for an orientation among heterogeneous distractors. We need to establish these basic phenomena with our particular stimuli before proceeding.

Method

Stimuli

In all experiments, subjects searched for an identified target line among distractor lines of different orientations. Stimuli were straight lines 2.0° in length and 0.3° in width. Stimuli were presented on a standard TV monitor (640 × 480 pixels) that was part of a modified "Sub-Roc 3-D" video game. Anti-aliasing techniques were used to eliminate the jaggedness of oblique lines. Displays were controlled by an IBM PC-XT with IBM-YODA graphics. Stimuli were presented in an 11.3° × 11.3° field with a small central fixation point. Subjects were asked to fixate, but eye movements were not monitored. Individual items could be presented at any of 16 locations in a slightly irregular 4 × 4 array. Four set sizes were used: 1,4, 8, and 12. *Set size* refers to the display set size, the number of items on the screen. On any given trial, the items were presented at randomly chosen loci. Targets were present on 50% of trials. On target trials, a target item replaced one of the distractor items, keeping the set size constant. Set size, positions of target and distractors, and presence or absence of a target were random across trials.

Trials were initiated by a left-thumb keypress. All stimuli were presented at the same time by adjusting a color look-up table. Because of video refresh, items at the top of the display could appear up to 17 ms before items at the bottom. Subjects responded by pressing one of two keys with the right hand: A *yes* key if a target was detected and a *no* key if it was not. The *yes* key was directly above the *no* key. Reaction times (RTs) were measured from the onset of the display. The stimuli remained visible until the subject responded, and feedback was given on each trial. In each condition, subjects were given 30 practice trials followed by 300 experimental trials. All experiments in this article were variations of this visual search paradigm.

There were four conditions in Experiment 1, two with homogeneous distractors and two with heterogeneous distractors. In the homogeneous conditions, subjects searched for a vertical (0°) target among distractors tilted 20° to the right of vertical, or, conversely, for a line tilted 20° to the right among vertical (0°) distractors. In the heterogeneous conditions, the target was again either 0° or 20°. The distractors were eight other orientations (either 0° or 20° and 40°, 60°, 80°, −20°, −40°, −60°, and −80°. We use negative values to designate orientations tilted to the left of vertical.). Distractors were chosen so that no orientation was duplicated in trials of Set Size 4 or 8, and no orientation was present more than twice in displays of Set Size 12. Figure 1 gives examples of two of the conditions, those with 20° targets. Each of the four conditions was run in a separate block of 330 trials. Subjects were shown the targets and distractors in advance of each block. Order of blocks was pseudorandom across subjects.

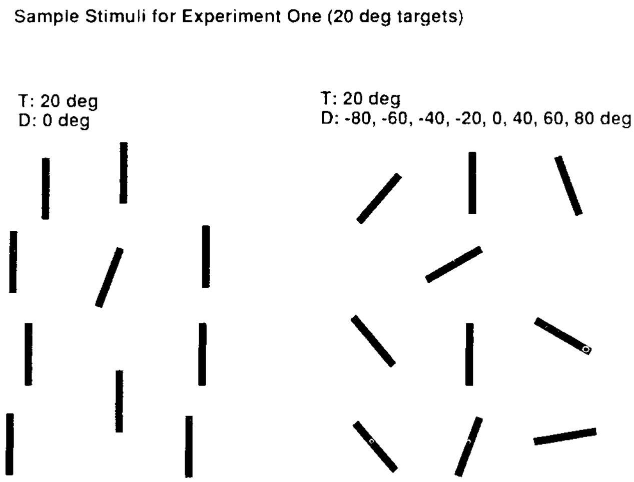

Figure 1. Sample stimuli for Experiment 1: Search for a 20° target is easy when distractors are homogeneous and hard when they are heterogeneous.

Subjects

Ten subjects were tested. Seven naive subjects were drawn from the Massachusetts Institute of Technology (MIT) subject pool. All gave informed consent and were paid for their participation. Three authors served as well-practiced subjects (JMW, SFH, and KMO). All 10 subjects had at least 20/20 acuity when wearing their best optical correction, if any.

Results

Average RTs and error rates (misses + false alarms) are shown in Figure 2. In this and subsequent figures, the range on the *y*-axis for the target trial data is half the range for the blank trial data. Slopes and slope ratios for each subject are shown in Table 1. Because Set Size 1 is a pure identification task and does not include a search task, slopes were computed by using Set Sizes 4, 8, and 12. We will follow this practice in all subsequent experiments. The searches with a homogeneous set of distractors are very efficient. The results replicate Treisman's finding of a search asymmetry: It is easier to find an oblique among verticals than vice versa (Treisman & Gormican, 1988). From an analysis of variance (ANOVA), RTs are longer for the vertical target trials, $F(1, 9) = 37.5$, $p < .001$; blank trials, $F(1, 9) = 17.5$, $p < .005$, and the blank trial slopes are significantly different from one another, paired one-tail *t* test, $t(9) = 2.5$, $p < .02$. The results for the searches with heterogeneous distractors replicate Moraglia's (1989) disordered array condition. The search for a vertical target yields average slopes of 19.7 ms/item for the target trials and 49.5 ms/item for the blank trials. This is only slightly better than Moraglia's 30 and 70 ms/item. The slopes are significantly greater than those for the same target with only one distractor orientation: paired one-tail *t* test, target trials, $t(9) = 2.8$, $p < .02$; blank trials, $t(9) = 3.1$, $p < .01$. The average ratio of blank to target trial slopes is 3.2:1. This is significantly greater than the 2:1 relationship predicted by serial, self-terminating search, one-sample *t* test, $t(9) = 1.9$, $p = .05$. There is a dramatic range of slopes for this task, with some subjects capable of very efficient searches and others not. Because there is no significant correlation between subjects' slopes and error rates, this would not appear to be due to a speed–accuracy trade-off. Individual differences will be discussed below.

The search for an oblique target among heterogeneous distractors is strikingly inefficient. The slopes are significantly steeper than those for the search for a vertical target among heterogeneous distractors: target trials, $t(9) = 5.8$, $p < .001$; blank trials, $t(9) = 8.1$, $p < .001$. The average ratio of blank to target trial slopes is 4:1. Because of the great variability across subjects, this is not significantly greater than the 2:1 relationship predicted by serial, self-terminating search, $t(9) = 1.2$, $p > .1$. There is no evidence for a speed–accuracy trade-off. Those subjects making more efficient searches do not make more errors.

Discussion

The most striking result of this experiment is the exceedingly steep slope for the search for an oblique among heterogeneous distractors. With slopes this steep, we must strongly suspect an eye movement artifact, at least on the part of some subjects. The eyes refixate about 4 times/s. Attention is thought to move about 15–25 times/s in visual search (e.g., Julesz & Bergen, 1983; Sagi & Julesz, 1986). Thus, slopes on the order of 200–250 ms/item for negative trials would suggest that items were examined not by covert movements of attention but by overt foveation of each stimulus. Slopes of 100–125 msec/item on blank trials would be expected if some subjects were processing two items per refixation. Eye movement artifacts will occur in visual search experiments any time the target and distractor stimuli cannot be differentiated in the periphery. Slopes of 250 ms/item could be produced with a search for vertical among horizontal if the lines were small enough. Nevertheless, a simple acuity limitation cannot explain the results of our experiment. If the targets could not be resolved in the peripheral visual field, then the other tasks (in particular the equivalent search for a vertical target) should have been similarly limited. Although the search for the vertical target is quite inefficient, it is nowhere near as slow as the search for the oblique target and is not within the speed range that allows the possibility of eye movements to each item or even to pairs of items.[2] Moreover, RTs for Set Size 1

[2] To demonstrate that eye movements were not necessary for tasks of this sort, we conducted a control experiment. Ten subjects searched for a target tilted 22° off vertical among 0° and 45° distractors (see Experiment 2 for a comparable condition). The average slopes were 52.7 ms/item for target trials and 100.0 ms/item for blank trials with some subjects showing clear indications of an eye movement artifact. We ran the same subjects on the same search but flashed the stimuli for either 100 or 500 ms. All subjects ran in all three conditions with the order of conditions counterbalanced across subjects. The screen flashed to white after the brief presentation to eliminate cues from phosphor persistence. The slopes were much shallower in the brief flash conditions: For 500–ms flashes, 13.5 ms/item for target trials and 18.2 ms/item for blank trials; for 100–ms flashes, 6.8 ms/item

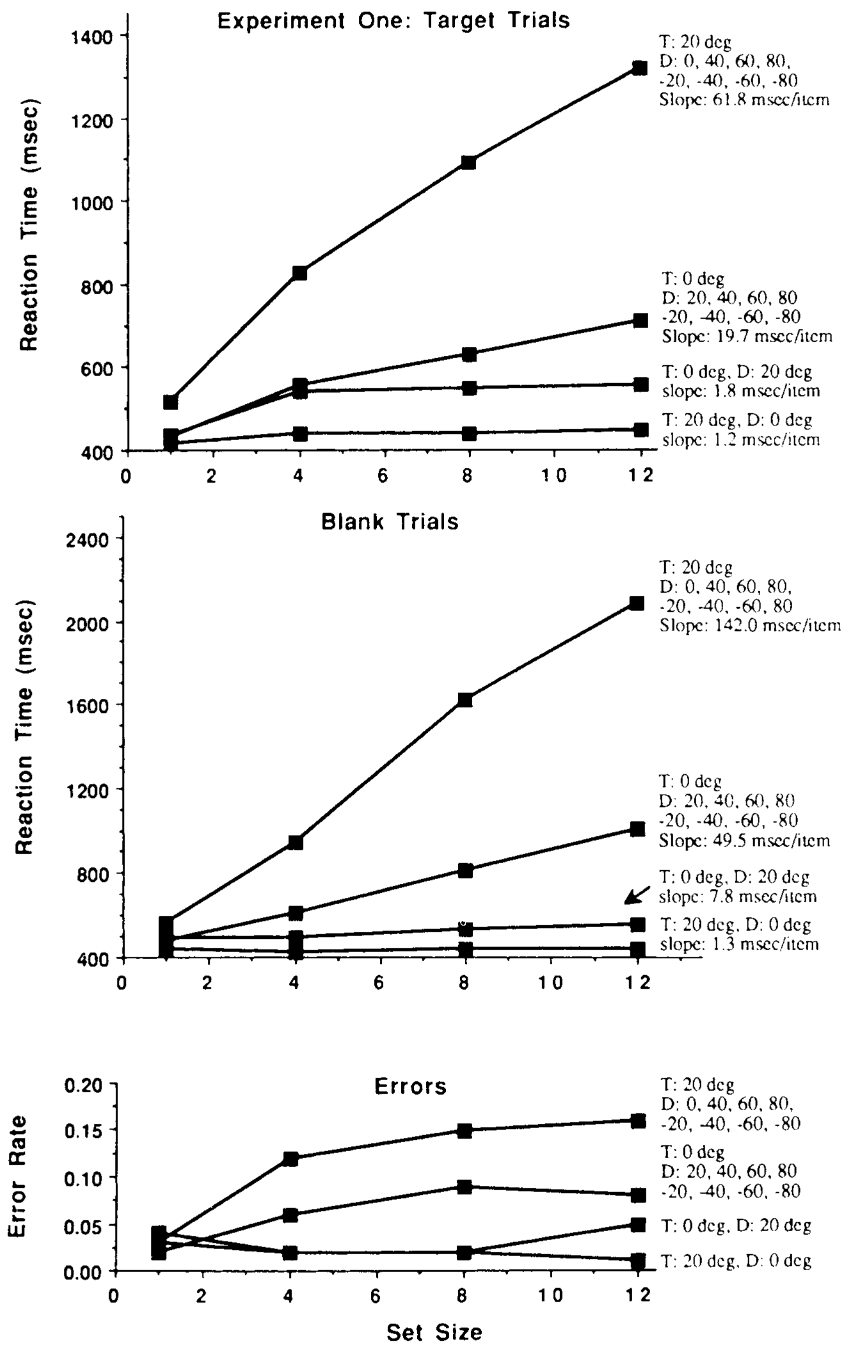

Figure 2. Results of Experiment 1: Searches for a single target orientation are essentially independent of set size when the target is presented among distractors of a single orientation. However, they are strongly dependent on set size when the distractors are heterogeneous. The effect of distractor heterogeneity is greater for oblique targets than for vertical targets.

for target trials and 7.3 ms/item for blank trials. Of course, the error rate increased markedly. However, it reached chance performance for only 3 subjects and then only at the highest set size. The results suggest that there is adequate information in the retinal image to do this task even without eye movements. The steep slopes in the continuous presentation condition suggest that most naive subjects are unwilling to commit to an answer on the basis of the information available in the periphery. Given the option, they move their eyes. In the absence of the option, their best guess is better than chance and is roughly consistent with a serial search at the usual attentional rate of 40–60 ms/item. Consider a 100-ms flash of a display of 12 items. In this time, attention should be able to examine 2 or 3 items. The other 9 or 10 items will be unexamined, but the subject will have a 50% chance of guessing correctly. Ignoring other sources of error and the possibility of processing more than one item in a single fixation of attention (Pashler, 1987), this yields an estimated error rate of 38%-42%. This drops to about 35% for Set Size 8 and 20% for Set Size 4. These predictions are comparable to our data.

Table 1
Slopes and Slope Ratios for Experiment 1

	Condition											
	Target trial slopes				Blank trial slopes				Blank/target ratios			
Subject	A	B	C	D	A	B	C	D	A	B	C	D
SFH	2.2	2.9	7.4	−1.8	18.6	55.6	−0.4	0	8.5	19.2	−0.1	0
MYG	5.1	54.0	0.9	−3.6	23.9	155.5	3.8	0.8	4.7	2.9	4.2	−0.2
JMW	8.8	42.8	2.8	−0.8	18.8	92.9	6.4	−0.6	2.1	2.2	2.3	0.8
KLS	11.9	69.0	11.6	−0.4	46.8	107.6	1.6	4.9	3.9	1.6	0.1	−12.2
KMO	12.9	64.9	−8.0	0.9	36.1	169.9	7.1	6.2	2.8	2.6	−0.9	6.9
JNS	15.8	65.6	−2.1	−1.5	36.4	153.1	23.1	−1.0	2.3	2.3	−11.0	0.7
KJN	19.0	72.1	−2.4	4.8	34.0	168.5	7.6	0.4	1.8	2.3	−3.2	0.1
MGS	21.0	36.5	5.4	6.2	24.5	94.1	3.4	0.6	1.2	2.6	0.6	0.1
ARP	35.0	63.2	1.9	3.0	99.8	158.9	13.6	−1.8	2.9	2.5	7.2	−0.6
MMB	65.6	147.4	0.6	5.4	156.1	263.4	11.5	3.1	2.4	1.8	19.2	0.6
M	19.7	61.8	1.8	1.2	49.5	142.0	7.8	1.3	3.3	4.0	1.8	−0.4

Conditions	Target	Distractors
A	0°	20°, 40°, 60°, 80°, −20°, −40°, −60°, −80°
B	20°	0°, 40°, 60°, 80°, −20°, −40°, −60°, −80°
C	0°	20°
D	20°	0°

are fast and comparable for all conditions, again arguing against a simple acuity limitation.

It seems more likely that the lines were interfering with one another in the periphery. Andriessen and Bouma (1976) looked at changes in the just-noticeable difference (jnd) for orientation in the presence of flanking stimuli in the periphery. Using lines parallel to the orientation of the test line, they found that the jnd could increase to as much as 20° or 30°. Gilbert and Wiesel (1990) found that lines placed well outside the classical receptive field of a cortical cell could radically change the orientation tuning of that cell. Some cells changed their preferred orientation, whereas others had their tuning curves broadened. Our conditions are not strictly comparable to either of these studies, but if the information about the orientation of a peripheral line is altered or degraded by the presence of other lines, then it is not surprising that some subjects resort to foveation to perform the task. To explain the difference between the search for an oblique target and the search for a vertical target among heterogeneous distractors, we must assume that the interference effect is weaker for vertical stimuli. Andriessen and Bouma (1976) have weak evidence of this sort (their Figure 8). The advantage for vertical could be caused by the preferential processing of main axis stimuli that underlies the oblique effect (Campbell, Kulikowski, & Levinson, 1966; Timney & Muir, 1976). It may also reflect categorical processing of the sort demonstrated later in this article. Treisman points in this direction in her account of the search asymmetry seen with homogeneous distractors. She suggests that it is easier to find a target with the attribute "tilted" than to find a target lacking that attribute. In the heterogeneous distractor case, however, most of the distractors are tilted. It may not be easy to find "not tilted" among "tilted," but it is certainly easier than finding one kind of tilted line among other tilted lines.

The results of Experiment 1 confirm that orientation information can support efficient visual search when one orientation is presented in an array of homogeneous distractors but not when that orientation is presented in a heterogeneous array. Given that the visual world generally contains many orientations, how is it possible to use orientation information in visual search? Perhaps the inefficient searches of Experiment 1 simply overloaded the system. In Experiment 2, similarly inefficient searches are found with only two distracting orientations.

Experiment 2: When Does Visual Search for Orientation Become Inefficient?

Method

There were four conditions in Experiment 2. As in Experiment 1, the targets were either 0° or 20°. In each condition, there were two flanking distractors. For two conditions, these were oriented 20° away from the target (i.e., target, 0°, distractors, −20°, 20°; target, 20°, distractors, 0°, 40°). For the other two conditions, the distractors were oriented 40° away from the target (i.e., target, 0°, distractors, −40°, 40°; target, 20°, distractors, −20°, 60°). Examples of the 20° target conditions are shown in Figure 3. In all other respects the experiments were identical to those in Experiment 1. Subjects in Experiment 2 were the same 10 subjects tested in Experiment 1. Indeed, the eight conditions of Experiments 1 and 2 were run together in pseudorandom fashion and are presented separately only for purposes of exposition.

Results

Average RTs and error rates are shown in Figure 4. Results for the heterogeneous distractor conditions of Experiment 1 are shown for comparison (dotted lines in Figure 4). Individual slopes and slope ratios are in Table 2. As in Experiment 1, there is substantial variation across subjects. The average target trial results for two distractors, ± 20° from the target

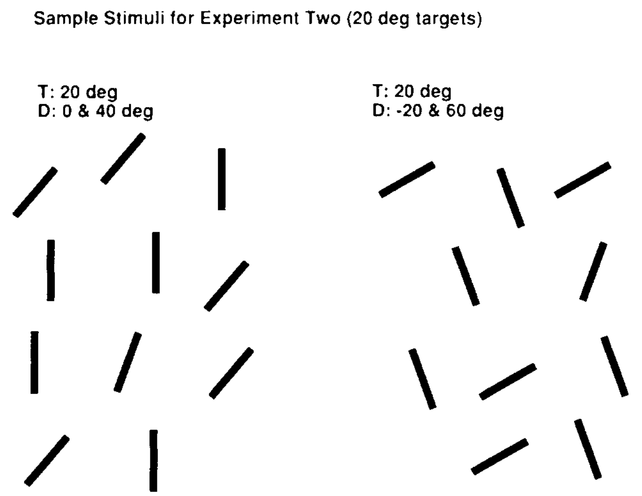

Figure 3. Sample stimuli for Experiment 2: Search for a 20° target remains hard with only two flanking distractor orientations, ± 20° or ± 40°.

orientation, are very similar to the results with eight heterogeneous distractors obtained in Experiment 1 and shown as dotted lines in Figure 4. Search for a vertical (0°) target is significantly easier than that for a 20° target with both ± 20° and ± 40° flanking distractors: all paired comparisons, $t(9) > 4.0$, $p < .005$. Not surprisingly, searches with 20° flanking distractors are more difficult than with 40° flanking distractors except for the blank trials with 20° targets. With the exception noted, for all paired comparisons, $t(9) > 4.3$, $p < .001$.

Discussion

Reducing the number of distractor orientations from eight to two does not markedly improve the efficiency of orientation searches. Target-present search trials with distractors 20° to either side of the target are very inefficient, comparable to the eight-distractor searches of Experiment 1. Blank trial searches may be somewhat more efficient, reflecting a greater willingness on the part of subjects to commit to a *no* answer in the two-distractor case.

There are large individual differences in performance on these tasks, though it is worth remembering that the significant effects across different experimental conditions exist in spite of this variability. In particular, the 3 practiced observers performed much more efficient searches. There are other cues that may be available to practiced observers. For example, when the target is 20° and the distractors are 0° and 40°, the distractors form only 40° angles with each other. The introduction of a 20° target item introduces more acute, 20° angles. It seems possible that this cue, rather than the orientation of the individual lines, was used in some cases. Such emergent cues are not the topic of this article and will be the subject of future research. For purposes of this article, the efficient performance of practiced subjects illustrates that even simple displays such as those used here may contain multiple cues, and practiced observers will tend to find any cue available.

The task does become easier as the distractors differ more from the target in orientation. However, even when the distractors are 40° away from the target, the search for a 20° target is still inefficient, producing slopes comparable to those in searches generally thought to be serial (e.g,. search for a T among Ls). With a 40° separation between targets and distractors, targets and distractors should be stimulating entirely different orientation channels (Thomas & Gille, 1979). This suggests that problems with search among heterogeneous distractors are not due entirely to the proximity in the orientation of target and distractors.

Of the four conditions in Experiment 2, the only easy search is the search for a 0° (vertical) target among ± 40° distractors. Introspectively, it seemed that this is a search for a steep item among relatively shallow items. By contrast, the search for a 20° target among −20° and 60° distractors is not easy because the target does not have any unique categorical label. The 20° target is steep, but so is the −20° distractor. The 20° target is tilted to the right, but so is the 60° distractor. The remaining experiments in this article demonstrate the validity of this intuition. Categorical status can influence visual search for orientation. Searches are more efficient when the target is the sole member of one category and the distractors all belong to some other, mutually exclusive category. In the following experiments, categorical terms will be used with their commonsense definitions (e.g. *steep* will refer to orientations closer to vertical). The categorical status of orientations around 45° is not clear. Though it will be a topic of future research, for the present, the borders between steep and shallow will remain fuzzy.

Experiment 3: "Steep" as a Category

Experiment 3 seeks evidence for the use of *steep* as a category by comparing three geometrically equivalent search tasks. Here "geometrically equivalent" means that the targets and distractors remain separated by the same angular differences across conditions although their absolute orientations change relative to the vertical and horizontal axes. Hence, all conditions are simple rotations of each other in the orientation domain. The conditions vary only in the categorical status of the items.

Method

Stimuli

Stimuli were lines 2.0° long and 0.3° wide. The two types of distractor items were oriented 60° clockwise and 40° counterclockwise from the target. The specific orientations for the three conditions were the following.

Steep. Target, −10°; distractor, −50°, 50°. Target is the only steep item.

Steepest. Target, 10°; distractor, −30°, 70°. Target is steepest but not the only steep item.

Steep–right. Target, 20°; distractor, 20°, 80°. Target is steep and "right."

The conditions are illustrated in Figure 5.

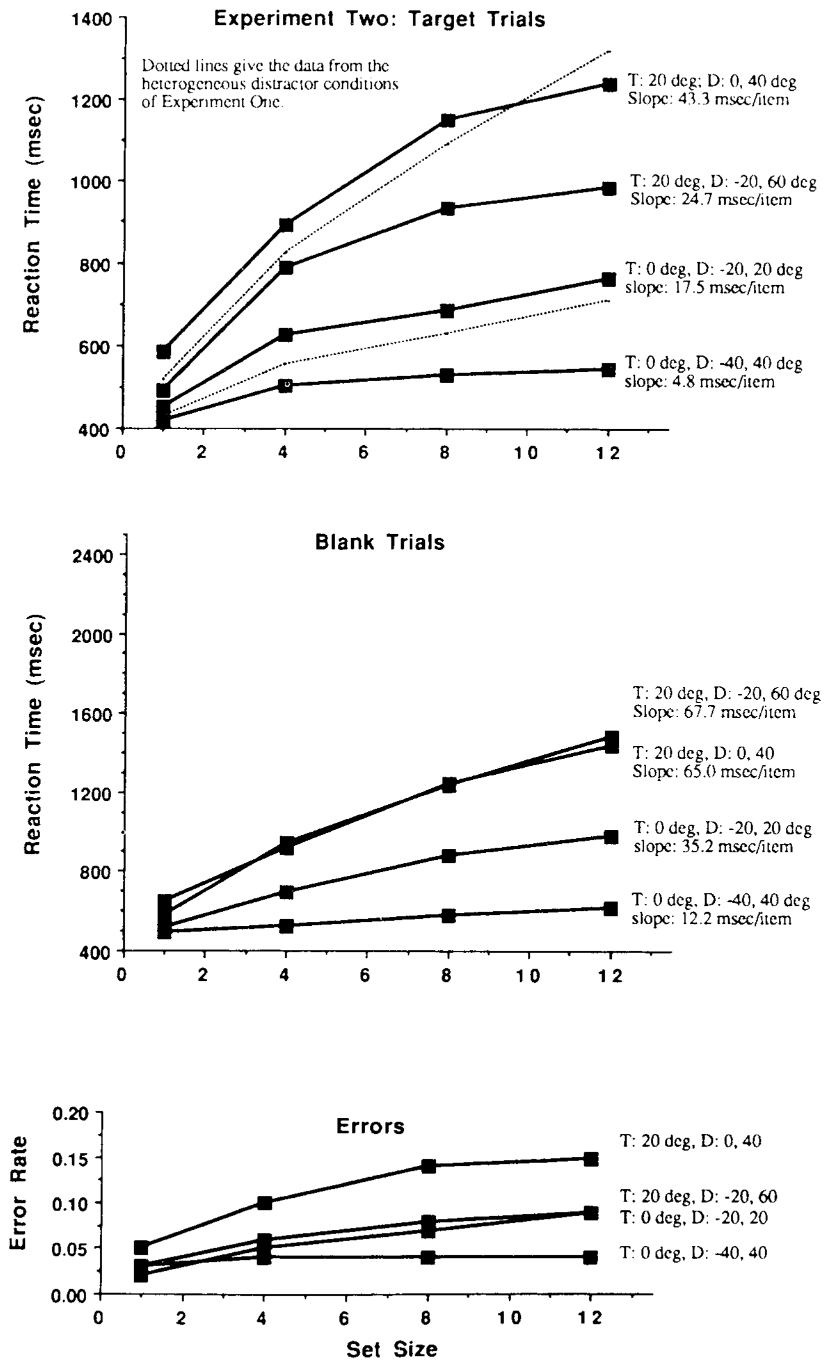

Figure 4. Results of Experiment 2: Effects of distractor heterogeneity remain strong even if only two flanking orientations are used as distractors. If the flanking orientations are moved 40° away from the target orientation, search remains inefficient except in the case of a vertical target among ± 40° distractors.

Subjects

Subjects were given the same type of instructions for all conditions. Subjects were shown the target and distractor stimuli and were asked to familiarize themselves with the distinctions between target and distractors. No specific strategy was suggested to the subjects. The words "steep," "steepest," and so forth were deliberately not used in the instructions. Order of conditions was randomized across subjects. Ten subjects from the MIT subject pool were tested. These did not include the authors. In all other respects, the methods followed previous experiments.

Results

Average RTs are given in Figure 6, and individual slopes are given in Table 3. The steep condition with a single steep

Table 2
Slopes and Slope Ratios for Experiment 2

	Condition											
	Target trial slopes				Blank trail slopes				Blank/target ratios			
Subject	A	B	C	D	A	B	C	D	A	B	C	D
SFH	6.6	21.6	−3.6	5.2	8.2	45.5	4.8	7.0	1.2	2.1	−1.3	1.3
MYG	24.6	26.6	1.0	29.9	24.5	53.9	8.4	101.6	1.0	2.0	8.4	3.4
JMW	6.9	18.2	3.1	4.1	26.6	43.2	7.6	37.8	3.9	2.4	2.5	9.2
KLS	10.4	65.9	8.0	51.5	21.2	67.4	6.5	84.9	2.0	1.0	0.8	1.6
KMO	14.8	16.5	1.5	−4.4	25.1	69.9	3.8	41.9	1.7	4.2	2.5	−9.5
JNS	12.6	60.6	8.1	25.6	38.8	90.4	7.2	65.1	3.1	1.5	0.9	2.5
KJN	24.6	52.1	10.2	27.5	31.8	68.8	17.1	56.5	1.3	1.3	1.7	2.1
MGS	18.9	41.6	2.9	43.4	58.8	69.8	14.9	68.5	3.1	1.7	5.1	1.6
ARP	27.5	64.8	6.0	29.5	44.2	50.1	31.8	66.5	1.6	0.8	5.3	2.3
MMB	28.0	64.9	10.8	34.2	73.0	91.6	19.5	146.9	2.6	1.4	1.8	4.3
M	17.5	43.3	4.8	24.7	35.2	65.0	12.2	67.7	2.2	1.8	2.8	1.9

Conditions	Target	Distractors
A	0°	−20°, 20°
B	20°	0°, 40°
C	0°	−40°, 40°
D	20°	−20°, 60°

target is significantly more efficient than either of the others. The results of paired *t* tests comparing slopes are given at the bottom of Table 3 for target and blank trials. Six of 10 subjects had target trial slopes less than 3.0 ms/item for the steep condition. Only 1 subject performed that efficiently for the steep–right condition; none for the steepest condition. Because of the considerable variability between subjects, we cannot reject the hypothesis that the blank/target slope ratios equal 2.0 for any condition. However, none of the conditions provides particularly convincing evidence for 2:1 slope ratios. Note that although there is variability across subjects, target trial slopes are shallower for the steep condition than in the steepest condition for 10 of 10 subjects. Steep condition slopes are shallower than steep–right slopes for 9 of 10 subjects.

Discussion

These results support the hypothesis that categorical status contributes to the efficiency of orientation search when the target is categorically different from the distractors. In this case, steep appears to be a category for purposes of orientation search. When the target is the only steep item, search is more efficient than it is in other geometrically equivalent conditions. This is particularly clear in the comparison between the steep and steepest conditions. The target, in both cases, is 10° from vertical. The distractors flank the target 40° to one side and 60° to the other. Yet these two very similar tasks yield different results. The sole steep item can be found more efficiently than the steepest item. Similar experiments suggest that shallow is also a category. We have not yet directly tested for any asymmetry between the potency of steep and shallow.

It is interesting to note that the steepest condition, in which the target is steeper than any distractor, is no better than the steep–right condition, where this cue is not available. In the presence of steep distractors, subjects did not appear to make use of the fact that the target was the steepest item. The steepest and steep–right conditions could also be described as conjunctions of the two orientation categories steep and right. We see little evidence for guided search in these conditions. In our previous work, we have shown that guidance of attention is possible for conjunctions between two feature types (e.g., Color × Orientation; see Wolfe et al., 1989) but not for conjunctions within a feature type (e.g., Color × Color; see Wolfe et al., 1990). The failure of subjects to guide search to steep right conjunctions suggests that steepness and direction of tilt are not separate features for purposes of visual search but rather categorical attributes within the basic feature of orientation just as red and green are categorical attributes within the basic feature of color.

Experiment 4: "Left" as a Category

Method

Experiment Four tests for the use of "left" as a category and replicates the use of *steep* as a category. The three conditions of Experiment Four are:

Left. Target, −30°; distractor, 10°, 90°. Target is the only left-tilted item.

Steep. Target, 10°; −50°, 50°. Target is the only steep item.

Steep–left. Target, −20°; distractor, 20°, −80°. Target is steep and left.

Steep and steep–left conditions are mirror images of two of the conditions in Experiment 3. The left condition is a simple rotation of the other conditions. Ten new subjects were drawn from the MIT subject pool. In all other respects, the experiment was identical to Experiment 3.

Results and Discussion

Average RTs are shown in Figure 7. Individual slopes and slope ratios are shown in Table 4. The left and steep conditions produce shallower target and blank trial slopes than the steep–left condition (paired *t* values are given in Table 4). The apparent advantage for left is not significant for target trials

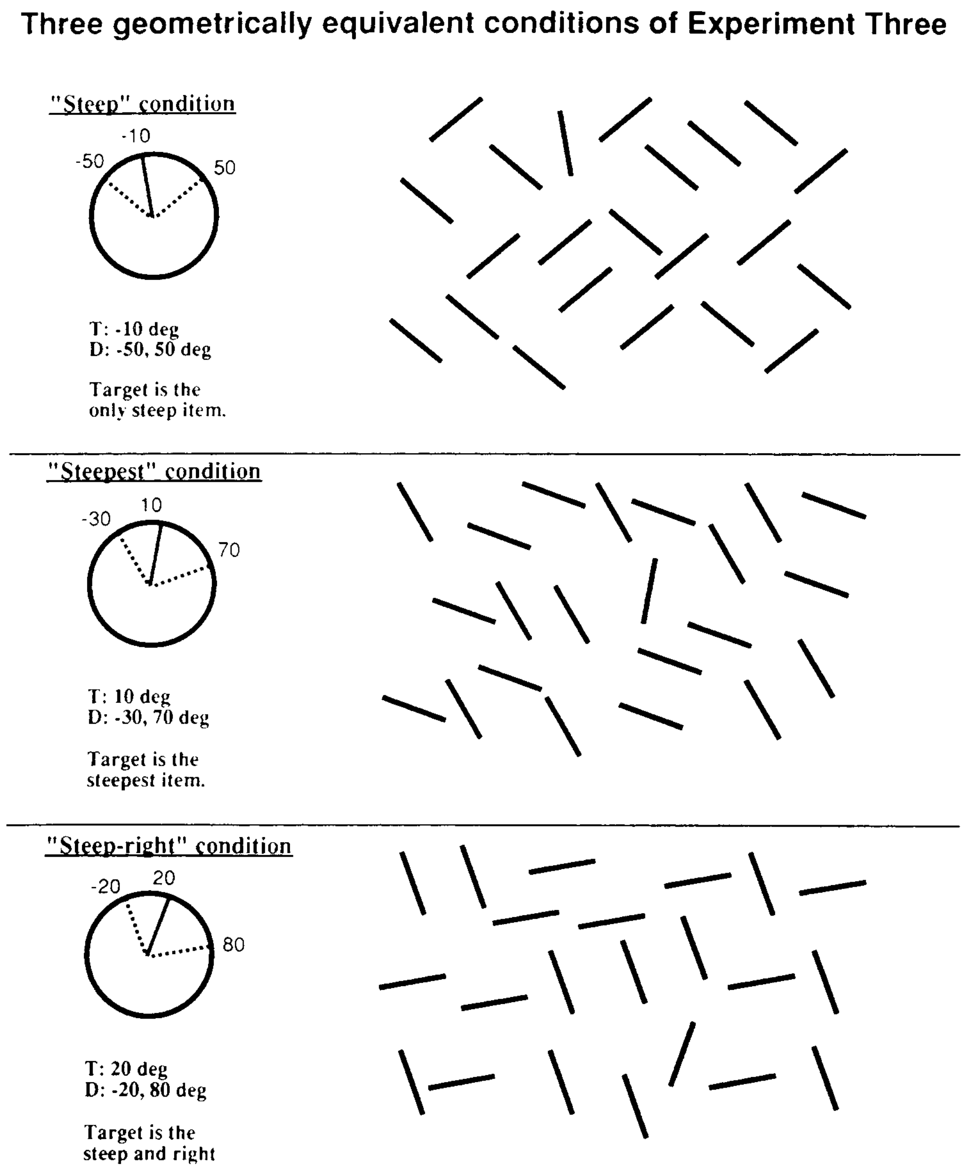

Figure 5. Stimuli for Experiment 3: All conditions are simple rotations of each other. Search is most efficient when the target possesses a unique categorical property (here, steep).

but is significant for blank trials. In other experiments in our lab, this apparent asymmetry is reversed, and it should not be considered a general rule. Slope ratios are wildly variable across subjects. We cannot reject the hypothesis that the ratios are 2:1, but that is neither surprising nor interesting.

The conclusions to be drawn from this experiment are analogous to those of the previous experiment, now applied to the left category (and, we assume, the right category). A target may be found more efficiently if it can be labeled as the only left-tilted item than if it cannot be so labeled. Again, note that a target that is a conjunction of left and steep cannot be found efficiently, unlike conjunctions between two different types of feature (Wolfe et al., 1989). Because one of the distractors in the left condition is horizontal, the condition could be considered a tilted condition if the 10° distractor is considered to be sufficiently similar to vertical (see Experiment 5). We have run other versions of the experiment with a uniquely left-tilted target and different, clearly tilted distractors. These yield results similar to the present experiment.

Experiment 5: "Tilt" as a Category

Treisman (1986; Treisman & Gormican, 1988), in her initial studies of orientation, noted that it was easier to find a tilted item among verticals than to find an item lying on the primary vertical or horizontal axes among tilted items. In Experiment 5, we establish that Treisman's conjecture holds for heterogeneous distractor sets. That is, tilted appears to have a stronger claim to categorical status than untilted.

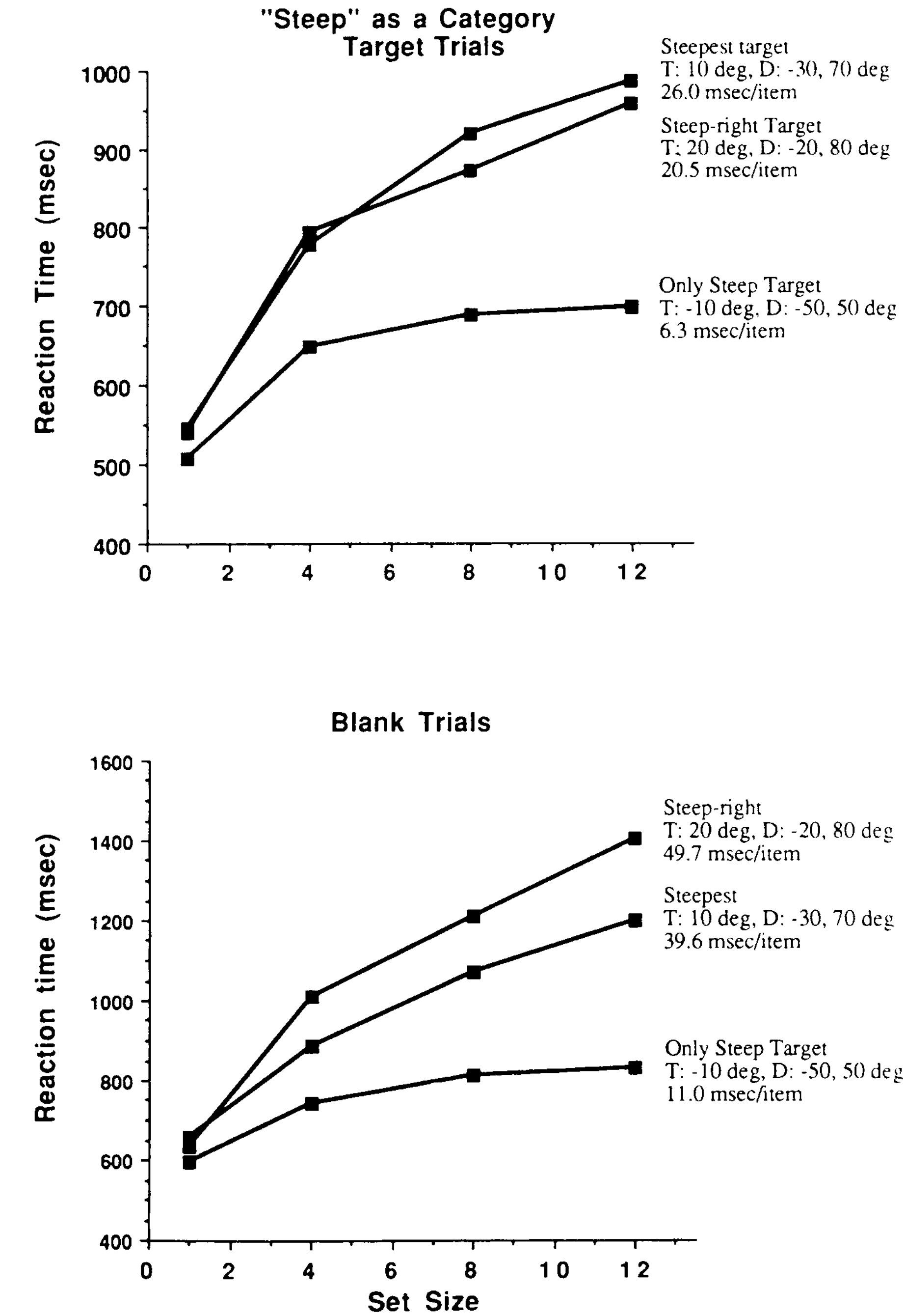

Figure 6. Results of Experiment 3: In the three searches presented here, one distractor type is always oriented 40° from the target, and the other is 60° in the opposite direction. The search is much more efficient when the target can be defined as the sole steep item even though all three tasks are geometrically equivalent.

Method

There were three conditions in Experiment 5. In these tasks more than one orientation could be the target, as shown in Table 5.

Note that Conditions Tilt2 and VH are simple rotations of one another following the design of the previous two experiments. Ten subjects from the MIT subject pool were tested. In all other respects, the methods of this experiment followed those of the previous experiments.

Results

It is clear from the data shown in Figure 8 that finding the tilted item among items that are either vertical or horizontal

Table 3
Slopes and Slope Ratios for Experiment 3 (Steep = A, Steepest = B, Steep-right = C)

	Target trial slopes			Blank trial slopes			Blank/target ratio		
Observer	A	B	C	A	B	C	A	B	C
SWC	−2.1	33.2	13.2	1.8	22.9	20.6	−0.8	0.7	1.6
DDG	−1.8	9.1	2.9	5.5	6.4	27.9	−3.1	0.7	9.6
BEC	−1.8	11.1	17.5	3.8	24.6	9.5	−2.1	2.2	0.5
MGS	0.9	5.9	11.6	1.4	18.6	7.1	1.6	3.2	0.6
AET	2.4	29.5	25.0	17.0	66.4	54.6	7.1	2.3	2.2
DPT	3.0	20.1	11.5	−5.8	7.4	41.0	−1.9	0.4	3.6
AJS	8.9	42.4	7.6	6.5	39.2	24.9	0.7	0.9	3.3
EHM	16.9	33.0	23.4	0.8	57.8	77.2	0.04	1.8	3.3
MB	17.5	23.9	29.9	18.9	14.8	137.9	1.1	0.6	4.6
SC	19.0	52.1	62.8	60.0	138.2	95.9	3.2	2.7	1.5
M	6.3	26.0	20.5	11.0	39.6	49.7	0.6	1.6	3.1
Paired *t* tests			$t(9)$	$p <$		$t(9)$		$p <$	
A–B			5.4	.001		3.5		.005	
A–C			2.6	.003		3.5		.005	
B–C			1.2	.15		0.7		.25	

is easy. Error rates were low (< 5% in all cases). Clearly, the slopes for Conditions Tilt2 and Tilt4 are not significantly greater than 0.0. The slopes for Condition VH are greater than 0.0: target trials, $t(9) = 4.1$, $p < .01$; blank trials, $t(9) = 4.4$, $p < .001$. Comparing slopes, the asymmetry between Conditions VH and the geometrically equivalent Tilt2 is significant: target trials, $t(9) = 2.1$, $p < .01$; blank trials, $t(9) = 4.4$, $p < .001$. One subject produced highly anomalous results in the VH task (slope of 41 ms/item for target trials). Removing that subject from the analysis does not alter the conclusion that the Tilt2 condition is more efficient than the VH condition: target trials, $t(8) = 2.3$, $p < .02$; blank trials, $t(8) = 4.2$, $p < .002$.

Discussion

The asymmetry between Tilt2 and VH conditions may reflect an asymmetry in perception. Although 45° and −45° targets are both tilted and similar to one another, vertical and horizontal are more clearly two distinct entities. Subjects may have been searching for two types of target in VH and only one in Tilt2. In the Tilt4 condition, four different targets can be searched for efficiently because all of them are tilted. If subjects are searching for two distinct entities in the VH condition, what are they? The results of Experiment 2 suggest that they are not vertical and horizontal. If subjects could search for vertical, then the search for vertical (0°) among ± 20° should have been efficient. More likely, for purposes of visual search, vertical is merely a very good steep stimulus and horizontal is a very good shallow stimulus. Both vertical and horizontal have the negative attribute of not being tilted, but as Treisman has shown, it is difficult to search for the absence of an attribute. Thus, when subjects search for a vertical or a horizontal stimulus, they must search for either of two attributes. This is reasonably efficient but not as efficient as the search for the single attribute of tilted.

Experiment 6: Further Evidence for a "Tilted" Category

Method

Given the ease of the search for ± 45° among 0° and 90°, it is interesting to consider a slightly different search task. The target is tilted 45° to the right. The distractors are 0°, 90°, and −45°. Thus, the orientations used are identical to the Tilt2 condition of Experiment 5, but −45° becomes a distractor. Ten new subjects were drawn from the MIT subject pool. In other respects the experiment was similar to previous experiments.

Results and Discussion

Average results are plotted as the dotted lines in Figure 8. The slopes for this search are strikingly inefficient: 21.2 ms/item for target trials and 52.5 ms/item for blank trials. The elimination of tilted as a useful category in this new condition seems to render the task far more difficult. One would think that right could be used as a categorical description of the target in this case. However, the left–right symmetry between the 45° target and the −45° distractor probably hampers the search. There is evidence that ± 45° are confusable. For example, Butler (1964) found that it took longer to discriminate a 45° tilted T from a −45° T than it did to discriminate an upright from an inverted T (see Corballis & Beale, 1976, for a general review). In other visual search experiments, we have found interference effects from distractors that are symmetrical with the target, and we are currently pursuing this topic.

General Discussion

The experiments presented in this article illustrate and begin to address a basic conundrum of visual search. Some parallel processing is necessary if visual search and visual processing in general are to occur in a reasonable amount of

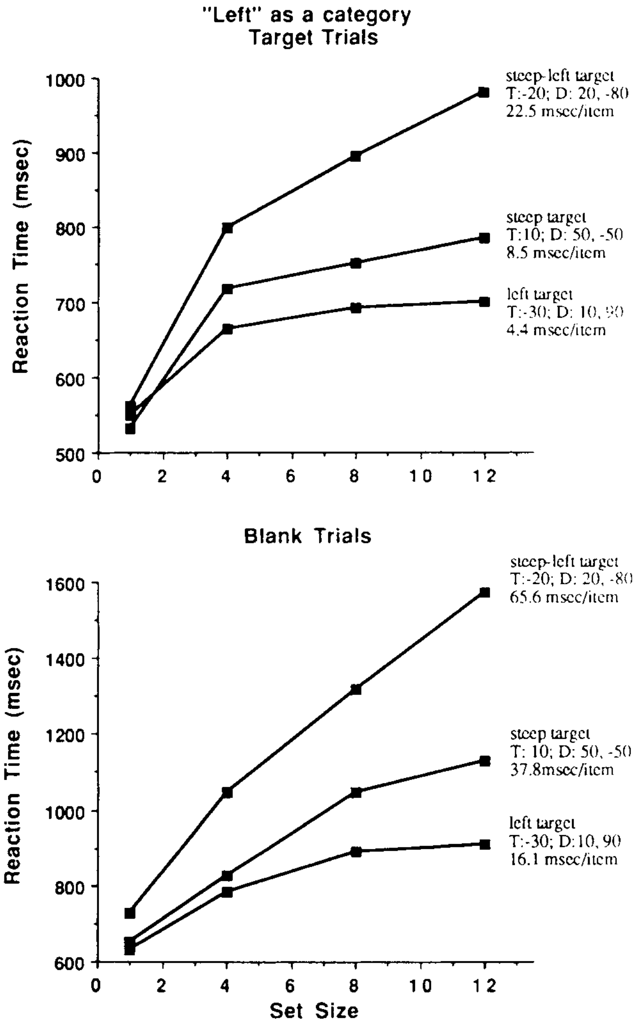

Figure 7. Results of Experiment 4: In the three searches presented here, the target is always oriented 40° from one distractor and 60° in the opposite direction from the other. The search is much more efficient when the target can be defined as the sole left or the sole steep item.

time. Parallel processing appears to break down in the face of stimulus heterogeneity, but the real world presents highly heterogeneous stimuli to the visual system. How then is the necessary parallel processing possible in real-world situations?

Part of the answer appears to be categorization. The effective heterogeneity of stimuli can be reduced if those stimuli are grouped into a small number of mutually exclusive categories. A search for 22° or −22° or 68° or −68° targets among 0° or 90° distractors might tax a visual system, but categorical recoding reduces the task to a simple search for a tilted target among untilted distractors (Experiment 5). Categorization in visual search is a specific example of a more general aspect of perceptual–cognitive processing. We continuously cope with the diversity of real-world stimuli by grouping those items into higher order categories like books, animals, and so forth.

The fact that categorization plays a role in visual search can be useful in localizing the mechanisms of search relative to other visual processes. Early visual processes are more closely tied to the physical geometry of the stimuli. Thus, for example, orientation discrimination is based on the distance in orientation between stimuli and not on their categorical status (Thomas & Gille, 1979). Visual search for orientation, by contrast, must occur at a locus in the system that has access to orientational categories and that does not appear to have direct access to the output of orientationally tuned channels in early vision. If the search apparatus could monitor these channels, we would expect that it would be easy to perform searches in which no distractor is closer than 40° (or even 20°) in orientation to the target. The separation between a categorical and a more continuous analysis of vision does not need to be hierarchical. One part of the brain could be doing a categorical task while another does a continuous task for a different purpose. There is some evidence for such a division of labor. Kosslyn et al. (1989) have shown a left hemisphere advantage in some categorical tasks (e.g., left–right or on–off judgments) and a right hemisphere advantage for a continuous distance judgment.

Categorization is undoubtedly not the only method available to the visual system to reduce effective complexity in visual search for orientation. We have found that most subjects can learn to do efficient searches in some cases where the target lacks unique categorical status. If the distractors form a texture (e.g., two orientations at right angles to each other), it may be possible to detect the target as a disruption of that texture. If there are other landmarks in the field, it may be possible to search for targets based on their orientation relative to the landmark. For example, in the experiments reported here, a square frame was always present at the outside of the field. When we rotated that border by 20°, subjects learned to search for a 20° target based on its alignment with the border and relatively independently of its categorical status. In general, the system is very resourceful and, with practice or direct instruction, will exploit any of a large number of cues.

This is not to say that the system is capable of using any and all possible cues. To give a few examples, we found that subjects could not ignore all items of one color even if that would provide a solution to a search task (Wolfe et al., 1990). Searches for a T among Ls, where the Ts and Ls are free to rotate, do not become parallel even with practice. Stimuli cannot be found on the basis of eye-of-origin information (Wolfe & Franzel, 1988). Thus, there are significant constraints on the mechanisms of visual search. Within those constraints, the mechanisms are very resourceful.

The availability of cues like categorization raises practical difficulties for models of visual search. Consider the concept of stimulus similarity central to Duncan and Humphreys's (1989) theory and, indeed, to our guided search model (Wolfe et al., 1989). It has always been difficult to know how to compare the distance in some similarity space between vertical and horizontal with the distance between red and green. The experiments presented here suggest that it may not be trivial to determine similarities even within a dimension. For instance, it seems that −30° and 20° may be more similar than −30° and 0°. Worse still, −30° and 20° may be similar when subjects' strategy is to search for steep or tilted items

Table 4
Slopes and Slope Ratios for Experiment 4 (Steep = A, Left = B, Steep-left = C)

	Target trial slopes			Blank trial slopes			Blank/target ratio		
Observer	A	B	C	A	B	C	A	B	C
SA	−1.8	−13.9	47.3	47.3	5.1	169.6	−26.3	−0.4	3.6
LO	−16.1	−3.9	−4.9	26.1	18.9	45.5	−1.6	−4.8	−9.3
ALH	11.5	−0.1	13.1	18.0	7.0	44.0	1.6	−70.0	3.4
MEJ	30.8	0.1	47.3	82.3	26.0	133.6	2.7	260.0	2.8
JDR	26.4	1.3	3.0	52.1	23.5	57.4	2.0	18.1	19.1
JBW	1.6	5.8	32.9	31.9	2.5	51.8	19.9	0.4	1.6
KDR	2.4	7.0	5.8	4.9	0.9	0.6	2.0	0.1	0.1
JML	2.1	11.3	27.9	38.6	12.1	47.6	18.4	1.1	1.7
CER	5.8	12.3	3.6	15.6	23.4	46.0	2.7	1.9	12.8
RS	22.1	23.9	49.1	61.4	42.0	59.9	2.8	1.8	1.2
M	8.5	4.4	22.5	37.8	16.1	65.6	2.4	20.8	3.7
	Paired *t* tests		$t(9)$		$p<$	$t(9)$		$p<$	
	A–B		0.9		.3	3.6		.005	
	A–C		2.2		.05	2.3		.05	
	B–C		2.5		.02	3.2		.01	

but dissimilar when subjects are searching for left-tilted items. This is not to suggest that similarity is a useless concept. It seems undoubtedly true, as Duncan and Humphreys (1989) state, that the efficiency of search increases with distractor–distractor similarity and decreases with target–distractor similarity. Though the principle may be true, the details will require careful experimentation on each feature in turn. Present data are fairly thin. A good example of the sort of experimentation that will be needed is the work of Nagy and Sanchez (1990), who have studied what amounts to target–distractor similarity for color. Furthermore, even if similarity metrics could be worked out for each feature, similarity considerations alone seem unlikely to be adequate to account for the results of conjunction search experiments (Treisman, 1991; Wolfe et al., 1990).

A number of specific issues remain open with regard to orientation categories.

In what frame are these categories specified? Left, right, steep, and shallow could be specified relative to retinal, head-centered, body-centered, gravitational, or environmental coordinates. Intuition suggests that these categories are relatively unaltered by moderate head tilt, but formal testing has yet to be conducted. As noted above, we have done some experiments tilting the frame around the stimuli, thus varying environmental coordinates. Subjects appear to be able to use the frame as a reference if that is useful.

How sharp are the categorical boundaries? Clearly 10° from vertical is steep. What about 40°? There are three logical possibilities. The border could be sharply drawn at 45° such that 40° is steep. There could be an ambiguous zone such that 40° is neither steep nor shallow (or where 40° is a weak example of steep). Finally, following the ideas of D'Zmura and Lennie (1988) in color, it may be possible to move the steep–shallow border within some limits, making 40° steep or shallow as needed.

Are categories learned? Experiments 3–5 present evidence for the categories left, right, steep, shallow, and tilted. The wide variability between subjects suggests that some subjects make better use of categorical information and other cues (e.g., angular relations) than other subjects do. Preliminary results from experiments with extensive practice suggest that all subjects can learn to use these cues. However, we could not find evidence for other categories (e.g., clock-face categories [1 o'clock, etc.]; see Dick & Hochstein, 1989). It remains an open question whether such categories could be taught with sufficiently extensive training.

Are all members of a category equivalent? In Experiment 3, steepest did not act as a separate category. This does not mean that 10° might not be a better example of steep than 30°.

Is categorization a bottom-up or top-down process? Orientation categorization could be subserved by a set of channels tuned for specific categories. That is, a steep channel might respond to all stimuli within 45° of vertical. Categorization could occur automatically with the presentation of stimuli. Alternatively, categorization could be a top-down strategy invoked when it is useful and not invoked when it would be ineffective. The apparent ability to switch strategies and to learn new strategies suggests top-down control, but this could reflect nothing more than an ability to choose to monitor one of several bottom-up channels.

Beyond orientation, the categorization of continuous input probably occurs for other features, though the requisite experiments have not yet been done. Consider color. Treisman (1988) and D'Zmura and Lennie (1988) have shown that it is hard to detect a color flanked by other colors in color space much as it is hard to search for an orientation flanked by

Table 5
Orientations for the Three Conditions of Experiment 5

Condition	Target	Distractor
VH	0°, 90°	−45°, 45°
Tilt 2	−45°, 45°	0°, 90°
Tilt 4	−68°, −22°, 22°, 68°	0°, 90°

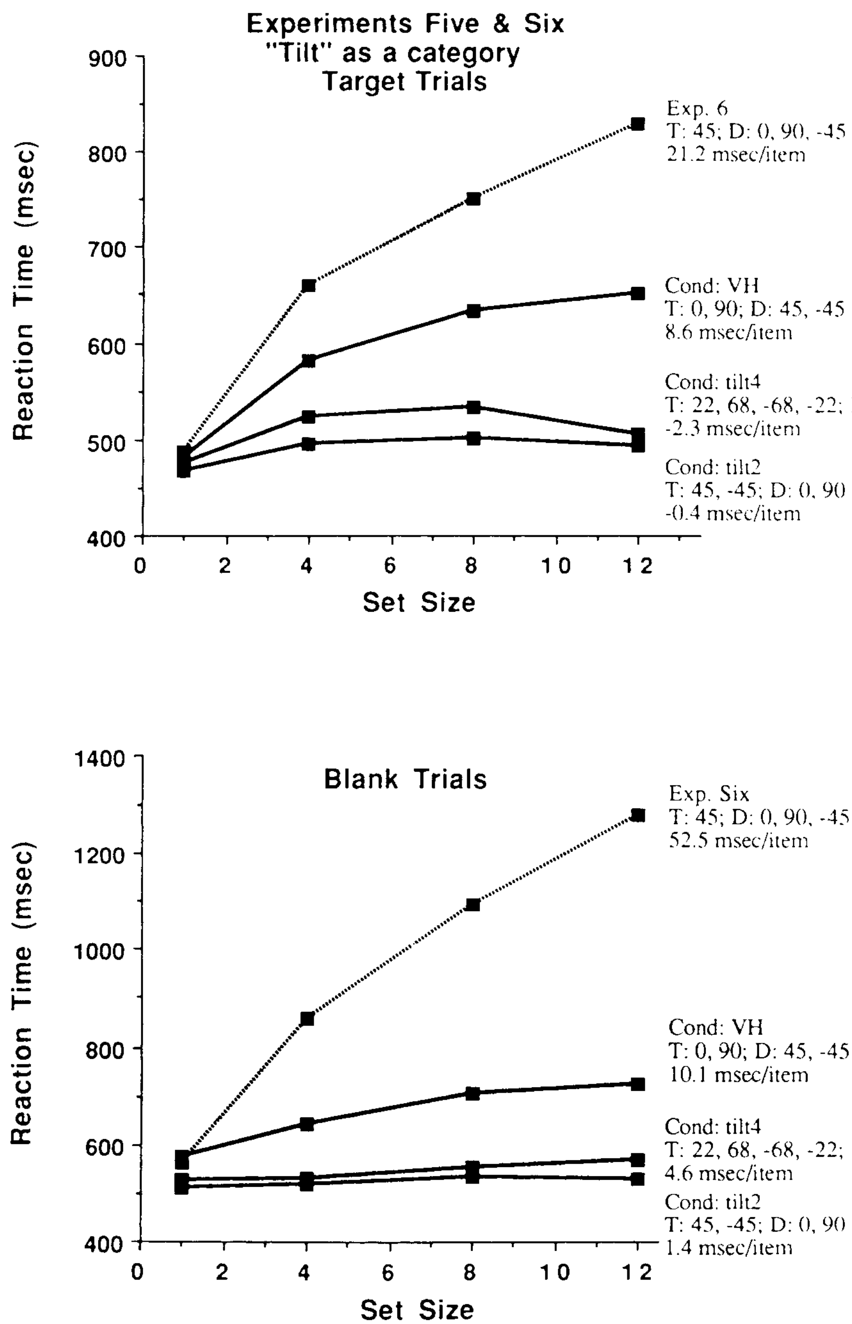

Figure 8. Results of Experiment 5: Search reaction times are relatively independent of set size if the target can be described as the sole tilted item. It is somewhat more difficult to find a target that can be either vertical or horizontal among tilted distractors.

distractors on either side in orientation space. D'Zmura and Lennie (1988) found that the location of the distractors in color space was critical and proposed a model that allowed for parallel search if and only if the color space could be partitioned by a straight line that placed the target color(s) on one side of the line and the distractor color(s) on the other. Color is more complex than orientation in that it has a two-dimensional feature space (three-dimensional if we include luminance). Moreover, that space can be represented in a number of different ways. If the appropriate space can be determined, it will be interesting to determine if color searches are more efficient when the targets and distractors straddle a categorical boundary than when they do not (cf. Sandell, Gross, & Bornstein, 1979).

Some dimensions may be simpler to study. Orientation forms an unusual one-dimensional feature space in that it is circular. It wraps around on itself through 180°. In other one-dimensional feature spaces, bottom-up considerations automatically generate two categories (e.g., faster and slower, bigger and smaller). These arise because any search where targets are to one side of distractors will give average distractor–distractor similarity that is greater than the average target–distractor similarity. Evidence for true categorization in such dimensions requires either efficient search for an intermediate target (e.g., medium size or speed) with distractors to either side in the feature space or evidence for a fixed boundary between big and small or slow and fast.

Finally, there are stimuli for which we do not know the feature space. Form is an obvious example. Braine's (1978) work in a different paradigm suggests that there may be form categories for upright, sideways and so forth, but it will be difficult to determine the nature of any form categories in visual search without a better model of form.

For purposes of visual search, the role of the parallel front end of the visual system is to direct attention to locations containing stimuli of interest. Because parallel processing is neuronally expensive (Tsotsos, 1990), it must be used sparingly. Apparently, under that constraint, the system lacks the ability to quickly direct attention to stimuli of a specific, arbitrary orientation. To operate successfully in a heterogeneous world, orientations can be categorized, effectively increasing the distractor–distractor similarity and decreasing target–distractor similarity. Attention can be guided on the basis of an item's categorical status. We may speculate that in the real world, a few broad categories are adequate to determine if a rock is placed in a stable position or if a picture is hung correctly on the wall. Similarly for other features, we believe it will be found that parallel processes categorize stimuli and guide attention on the basis of that categorization.

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Zahn-Waxler Appointed New Editor, 1993–1998

The Publications and Communications Board of the American Psychological Association announces the appointment of Carolyn Zahn-Waxler as editor of *Developmental Psychology.* Zahn-Waxler is associated with the National Institute of Mental Health. As of January 1, 1992, manuscripts should be directed to

Carolyn Zahn-Waxler
4305 Dresden Street
Kensington, Maryland 20895

Manuscript submission patterns make the precise date of completion of the 1992 volume uncertain. The current editor will receive and consider manuscripts through December 1991. Should the 1992 volume be completed before that date, manuscripts will be redirected to the incoming editor for consideration in the 1993 volume.