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# Visual search for oriented lines: The role of angular relations between targets and distractors

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**Abstract**—Subjects can perform parallel visual search for an item of unique orientation when it is presented on a background texture composed of lines of two other orientations. A number of cues can be used to speed this search. It helps if the target has a unique categorical status (e.g., it is the only 'steep' item) (Wolfe *et al., J. Exp. Psychol. Hum. Percept. Perf.* **18**, 34–49 1992). It helps if the two background orientations are symmetrical about a vertical axis (Wolfe and Friedman-Hill, *Psychol. Sci.* **3**, 194–198, 1992). The experiments presented here show that it helps if the angles formed by the target with one of the distractor types are smaller than the angles formed by the two distractor orientations. These results illustrate that stimulus similarity is a complex concept even for a simple feature like orientation.

It is possible to divide visual processing into pre- and post-attentive stages (Neisser, 1967). In the initial high-capacity, pre-attentive stage, visual processes seem to be able to handle information about a limited set of basic features in parallel across large portions of the visual field. In the subsequent, limited-capacity stage, processes can perform more elaborate perceptual tasks but only on a more restricted portion of the visual field at any one time. The serial deployment of this limited resource is under attentional control (Neisser, 1967; Treisman and Gelade, 1980; Julesz, 1981 and 1984). Information gathered by the parallel first stage *guides* attention and thus prevents the second stage from processing stimuli in a completely random order (Wolfe *et al.*, 1989; Cave and Wolfe, 1990).

In guiding attention, an important task for the first stage is to distinguish potential targets from a distracting background. A target may be a specified item (e.g., a search for a 'red X') or it may be an unusual item that attracts attention by virtue of its scarcity (e.g., a search for an 'odd-man-out' in a field of identical distractors). Odd-man-out search is easy if the target is a unique item placed among homogeneous distracting items and if the target differs from the distractors in some basic attribute such as color, depth, size, or orientation (Treisman and Souther, 1985). Under these conditions, search time is fast (*c.* 400–600 ms for many such tasks) and roughly independent of the number of items.

In real-world situations, the background is rarely homogeneous or completely random. The non-random distributions of basic features like color, orientation, or size create background textures against which we attempt to find targets. When heterogeneous distractors have been used in feature search experiments, the usual result has been less efficient search (e.g., orientation—Moraglia, 1989; Alkhateeb *et al.*, 1990; Wolfe *et al.*, 1992, color—Duncan, 1989; D'Zmura, 1991). In many of these cases, distractor heterogeneity produces an apparently serial, item-by-item search at a rate of about 40–60 ms/item (Bergen and Julesz, 1983).

We are presented with a puzzle. Real-world searches appear to proceed in a reasonably efficient manner in the presence of heterogeneous, textured backgrounds. Visual search experiments have shown that quite limited distractor heterogeneity (e.g., two types of distractors) can be enough to force an apparently serial search. These effects can be summarized in terms of stimulus similarity (Goldmeier, 1972; Tversky, 1977), a concept that has recently generated significant interest in the visual search literature (Duncan and Humphreys, 1989; Treisman, 1990). Specifically, Duncan and Humphreys (1989) have noted that visual search for a feature is harder when the target is similar to the distractors and easier when the distractors are similar to each other.

For this idea to have predictive power, we must know what it means for two stimuli to be 'similar' for purposes of visual search. The more similar two items are, the more difficult it should be to search for one as target with the other as a distractor. Further, the more similar two items are, the easier it should be to search for a third item in a distractor set composed of the first two types of item. In a series of recent papers, using this operational definition of similarity, we have been attempting to understand similarity for one basic feature, orientation.

At first glance, it might seem that orientational similarity between two lines should be a simple function of their angular separation. This is not the case. In addition to simple angular separation, similarity between lines of different orientations is influenced by the categorical status of the line orientations (i.e. whether the line is 'steep', 'shallow', 'tilted left' or 'right'—Wolfe *et al.*, 1992). Two 'steep' lines are more similar to each other than a 'steep' and a 'shallow' line even if the angular separations between the two pairs are the same. Similarity is also influenced by symmetry relations between orientations. Any two lines are symmetrical about some axis. In visual search, two lines are more similar to each other if they are symmetrical about a vertical (or, equivalently, a horizontal) axis than if they are symmetrical about some tilted axis (Wolfe and Friedman-Hill, 1992).

In the present paper, we demonstrate that the relationships between target and distractor orientations can act in a fashion *opposite* to the predictions of a similarity metric based on angular difference. Specifically, we show that search is faster when the angular separation between the target orientation and a distractor orientation is *smaller* than the angular separation between distractors of different orientations. Figure 1 illustrates this angular separation cue for a condition with two distractor orientations and one target orientation. In addition, the two other modulators of orientational similarity—categorical status and symmetry are shown.

The complex nature of similarity, even for a simple feature like orientation, illustrates the need to avoid untested assumptions about similarity in visual search experiments.

## EXPERIMENT 1

### *Methods and apparatus*

In all conditions of this experiment, the basic task was the same. Subjects searched for a line segment of unique orientation among distractors of two other orientations. The separation in orientation between two distractor orientations can be described by either of two angles: an acute angle of 90 deg or less and an obtuse angle of 180 deg minus the acute angle. Similarly, the target orientation will form a pair of angles with each distractor orientation. If the smallest target–distractor angle is smaller than the

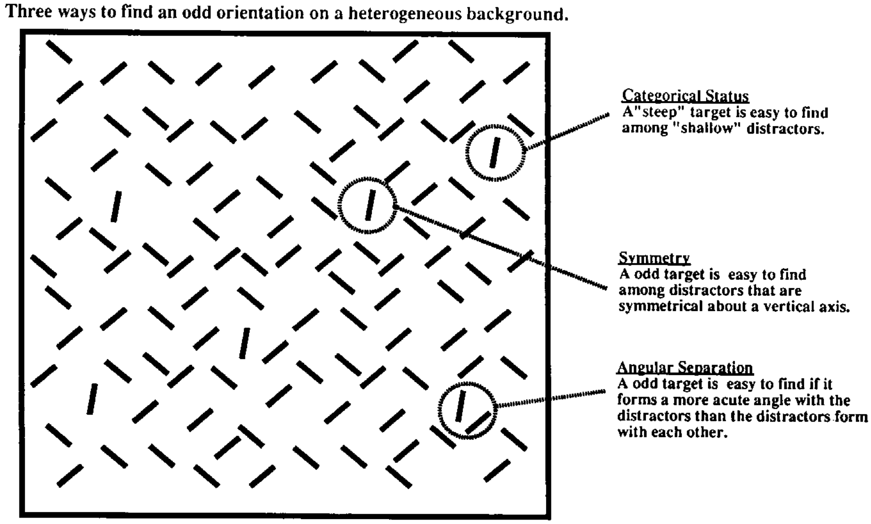


**Figure 1.** In this figure the targets are items tilted 10 deg to the right of vertical. The two distractor types are tilted 50 deg to the left and right of vertical. Subjects can use at least three strategies to find targets: (1) The target has a unique categorical status ('steep' among 'shallow' distractors); (2) The distractors are symmetrical about a vertical axis while the target *breaks* that symmetry; and (3) The target forms smaller angles with the distractors (40 and 60 deg) than the distractors form with each other (80 deg). This angular separation cue is the subject of the experiments reported here.

acute distractor–distractor angle, search is more efficient than if this relationship does not hold, all other factors being held constant.

This is *not* a search for a line of specific orientation. This is an 'odd-man-out' search for a target item of unique but variable orientation among two distractors of variable orientations. The target and distractor orientations varied from trial to trial. Subjects were tested on three blocks of trials. Order of blocks varied pseudorandomly across subjects. In each block, there were eight possible pairings of one target and two distractor orientations. These are shown in Table 1. In the Control or baseline condition, the smallest target–distractor (T–D) angle was within 10 deg of the distractor–distractor (D–D) angle for six of the eight target-distractor pairings. Pilot data suggested that 10 deg differences in angular separation were not a useful cue to target presence. Given random presentation of the different pairings, the angular separation was not a reliable source of information in this condition. The pairings were also designed so that the target never had a unique categorical status. Moreover, there was no vertical symmetry between target and distractors or between the two distractors.

The main experimental condition is the Smaller Angle condition. For each pairing of one target and two distractor orientations in the Smaller Angle condition, the target and one of the distractors were the same as in the Control condition (D2 in Table 1). The orientation of the other distractor was changed in order to make angular separation a reliable cue to the presence of a target. Specifically, the T–D difference in orientation was always at least 40 deg less than the D–D difference. Again, no targets had unique categorical status and there was no vertical T–D or D–D symmetry.[1]

**Table 1.**

Stimuli used in Experiment 1. T = target orientations, D1 and D2 = distractor orientations, cat = categorical status of target, sym = presence or absence of distractor symmetry about a vertical axis, T–D = smaller target–distractor difference, D–D = distractor–distractor difference

Control condition

| | | | | | | Angles | |
|---|---|---|---|---|---|---|---|
| Pair | T | D1 | D2 | cat | sym | T–D | D–D |
| 1 | −10 | −30 | −60 | no | no | 20 | 30 |
| 2 | −30 | 40 | −70 | no | no | 40 | 70 |
| 3 | −60 | −10 | 50 | no | no | 50 | 60 |
| 4 | −80 | −60 | −30 | no | no | 20 | 30 |
| 5 | 50 | 80 | −30 | no | no | 30 | 70 |
| 6 | 80 | 50 | 20 | no | no | 30 | 30 |
| 7 | 20 | −40 | 80 | no | no | 60 | 60 |
| 8 | 70 | 50 | 20 | no | no | 20 | 30 |

Smaller Angle condition
T and D2 same as Control. Only D1 is changed

| | | | | | | Angles | |
|---|---|---|---|---|---|---|---|
| Pair | T | D1 | D2 | cat | sym | T–D | D–D |
| 1 | −10 | 30 | −60 | no | no | 40 | 90 |
| 2 | −30 | −10 | −70 | no | no | 20 | 60 |
| 3 | −60 | −30 | 50 | no | no | 30 | 80 |
| 4 | −80 | 70 | −30 | no | no | 30 | 80 |
| 5 | 50 | 80 | −30 | no | no | 30 | 70 |
| 6 | 80 | −60 | 20 | no | no | 40 | 80 |
| 7 | 20 | −10 | 80 | no | no | 30 | 90 |
| 8 | 70 | 90 | 20 | no | no | 20 | 70 |

Steep-or-Right condition
The eight pairings in the Control condition are each rotated to produce pairings where the target is either the only 'right' tilted or the only 'steep' item

| Pair | T | D1 | D2 | rot | cat | sym |
|---|---|---|---|---|---|---|
| 1 | **20** | **0** | −30 | 30 | right | no |
| 2 | **40** | **−70** | 0 | 70 | right | no |
| 3 | **60** | **−70** | −10 | −60 | right | no |
| 4 | **70** | **90** | −60 | −30 | right | no |
| 5 | **30** | **60** | −50 | −20 | steep | no |
| 6 | **−20** | **−50** | −80 | 80 | steep | no |
| 7 | **10** | **−50** | 70 | −10 | steep | no |
| 8 | −40 | −60 | 90 | 70 | steep | no |

For purposes of comparison, a third condition was run. This Steep-or-Right condition made categorical information available as a cue. The target was always either the only 'steep' item or the only 'right' tilted item. The target–distractor pairings in the Steep-or-Right condition were obtained by adding a constant to the target and distractor orientations in the Control condition pairings.

To work through a single example for all three conditions, consider pairing number 1 in Table 1. In the Control condition the target was −10 deg and all the distractors were either −30 or −60 deg. (Orientations are relative to 0 deg vertical with positive values tilted clockwise to the right.) To generate stimuli for the Smaller Angle condition, the −30 deg distractor was changed to a 30 deg distractor. The D–D angle became 90 deg and the T–D angles were smaller; 40 and 50 deg. To generate stimuli for the Steep-or-Right condition, the original Control condition stimuli were rotated 30 deg clockwise. This yielded a 20 deg target among 0 and −30 deg distractors. The target became the only item tilted to the right. Similar transformations were used to generate all the stimuli in this experiment.

Subjects were asked to determine if two orientations were present or if an element of a unique third orientation was also present. In addition, for the Steep-or-Right and Smaller Angle conditions, subjects were given explicit instructions about the available category and angle size cues. In pilot work, we found that many subjects could discover categorical or angle cues without instruction. However, in this study we provided explicit instructions because our interest was in the ability to use this information and not in the ability to discover its presence.[2] Each block consisted of 330 trials. The first 30 were practice. Trials were divided randomly between four display set sizes of 4, 8, 12, or 16 items. A target was present on 50% of the trials. The remaining items were divided evenly between the two distractor orientations.

Stimuli were presented on a standard TV monitor (640 × 480 pixels) that happened to be part of a modified 'Sub-Roc 3-D' video game. Displays were controlled by an IBM PC-XT with IBM-YODA graphics. Viewing was binocular. Stimuli were straight lines 2.0 deg in length and 0.3 deg in width. They were red (luminance = 0.65 $cd/m^2$; CIE (1931) coordinates: 0.63, 0.35) on a dark background. Anti-aliasing techniques were used to eliminate the jaggedness of oblique lines. Stimuli were presented in an 11.3 × 11.3 deg 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 4 × 4 array that was made slightly irregular by allowing the position of items to vary by ±8 pixels.

### *Subjects*

Nine subjects were tested. All had 20/20 acuity when wearing their best correction. All gave informed consent and were paid for their time. Many had been subjects in previous visual search experiments but all were naive as to the specific design and purposes of this experiment.

### *Results*

Average results for all nine subjects are shown in Fig. 2. Looking first at the Control condition, the task is quite difficult but response times (RTs) are roughly independent of set size for set sizes larger than four. Target-present and target-absent (blank) trials are not significantly different (ANOVA: $F(1,8) = 0.138$, $P > 0.5$). Subjectively, the impression is of slowly determining that the items do or do not form a uniform texture. Displays containing only a few items (e.g., set size 4) do not form textures as well as more dense displays do. Consequently, for sparse displays, the task seems to be done by comparing each item with all other items in order to find an item of unique orientation.

In the Smaller Angle condition, when one (or both) T–D angle is always smaller than the D–D angle, search is faster. RTs for the Smaller Angle condition are significantly faster than those for the Control condition (ANOVA: target trials: $F(1,8) = 22.5$, $P < 0.001$; blank trials: $F(1,8) = 12.2$, $P < 0.01$). Again, target-present and target-absent (blank) trials are not significantly different (ANOVA:

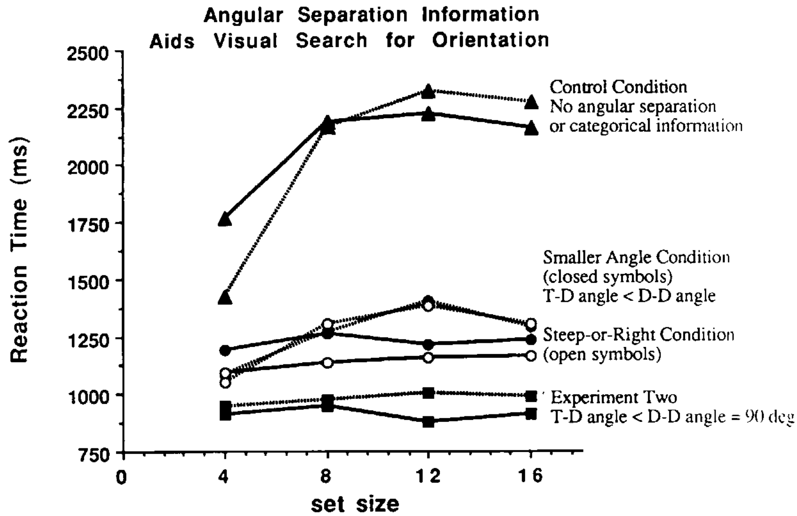


**Figure 2.** Average data for a visual search for a target of one orientation among distractors of two other orientations. Orientations change from trial to trial as described in the text and in Table 1. Conditions differ in cues available. The presence of an angular separation cue in the Smaller Angle condition and in Experiment 2 improves performance relative to a Control condition lacking that cue. The presence of a categorical cue in the Steep-or-Right condition also improves performance replicating a previous result (Wolfe *et al.*, 1992). Solid lines are target-present trials. Dashed lines are target-absent trials.

$F(1,8) = 1.0, P > 0.3$). Slopes for the target trials are not significantly different from 0.0 ms/item ($t(8) = 0.2$, $P > 0.75$). Blank trial slopes are greater than 0.0 ($t(8) = 2.3$, $P < 0.05$). Search is speeded if the target possesses a unique categorical attribute, even if that attribute is not constant across trials. Results from the Steep-or-Right categorical condition are comparable to those in the Smaller Angle condition. The RTs are significantly faster than the Control condition (ANOVA: target trials: $F(1,8) = 19.2$, $P < 0.005$; blank trials: $F(1,8) = 18.4$, $P < 0.005$) but not significantly different than the Angle condition (ANOVA: target trials: $F(1,8) = 0.6$, $P > 0.4$; blank trials: $F(1,8) = 0.0$, $P > 0.9$).

### *Discussion*

The subjects' task is the same for all three conditions in this experiment. Two distractor orientations form a background texture and the subject must detect the presence of a target disrupting that texture. Subjects cannot look for a specific orientation because the orientations change from trial to trial. They cannot look for a specific T–D or D–D angular separation because those separations vary from trial to trial. Though the task is comparable in all three conditions, the Smaller Angle and Steep-or-Right conditions are faster than the Control condition. The difference between the Smaller Angle and Control conditions is that the D–D angular separation has been *increased* in the Smaller Angle condition. This should act to slow search if similarity was a simple function of angular separation. Instead, it makes the search easier, perhaps by permitting search to be done on the basis of the size of the T–D and D–D angles. Subjects report being able to search for the smaller angle in the Smaller Angle condition. This cue is not available in the Control condition.

The Steep-or-Right condition replicates the previous finding that categorical information can be used to speed search (Wolfe *et al.*, 1992). In the context of the present paper, it serves to show that the angular separation cue yields improvement in search comparable to that obtained with categorical information.

## EXPERIMENT 2

In order to strengthen the argument that angular separation information is available in visual search tasks, we repeated the Smaller Angle condition of Experiment 1 with a few modifications on a new set of subjects. In this version, the distractor–distractor angle was held constant at 90 deg and the target was always 40 deg clockwise from one distractor and 50 deg counterclockwise from the other. Within those constraints, orientation was random across trials. Ten new subjects were tested. In all other respects, the experiment was identical to the Smaller Angle condition of Experiment 1.

The results are plotted in Fig. 2. The results are comparable to the Smaller Angle condition of Experiment 1. RT is independent of set size (ANOVA: $F(3,27) = 0.4$, $P > 0.75$). The fixed angles of Experiment 2 may make this version somewhat faster than the Smaller Angle condition of Experiment 1. However, this is only suggestive as unpaired $t$-tests comparing the $y$-intercepts for the two conditions are not significantly different (unpaired $t(17) = 1.4$, $P = 0.09$).

## GENERAL DISCUSSION

Stimulus similarity is an important concept in the understanding of feature searches. Most of the systematic empirical work has been done with one distractor type and one target type (e.g., color—Nagy and Sanchez, 1990, orientation—Foster and Ward, 1991a, and b). D'Zmura has extended this work to two types of distractor for color (D'Zmura, 1991), albeit from a somewhat different theoretical slant. Alkhateeb *et al.* have done some systematic work with two distractor orientations (Alkhateeb *et al.*, 1990). In this paper and others, we, too, have examined the issue for orientation. Several conclusions can be drawn from our results.

(1) Parallel processing is possible even when the target and distractor orientations are not known and the distractors are not homogeneous. In the absence of other cues, this parallel processing is very slow, at least for stimuli of the sort used here. Simple orientation feature searches produce RTs of about 500 ms with these stimuli (Wolfe and Cave, 1989). The Control condition RTs are about 1700 ms longer. Taking the usual estimate of 40–60 ms/item for serial processing of items (Bergen *et al.*, 1983), 30–40 items could be processed in series in that time. With an unknown target and heterogeneous distractors, items need to be compared to other items rather than being processed independently. Although it is possible to design algorithms that will do this task with fewer than 30–40 serial comparisons, our subjects do not appear to have done so. It may be that the memory demands of such strategies exceed what is available to the processes performing the task.

(2) Similarity becomes a more complex matter when the number of distractor orientations is increased from one to two. A definition of similarity based on angular separation cannot be adequate as the results from these experiments show that search can become faster when D–D angular separation is increased. The size of the T–D angle relative to the D–D angle provides information that can shave about a second off the average RT, a truly massive effect compared to most in this field. We do not

know if the angle information is computed locally, by comparing the angles formed by neighboring items, or globally across the field. The similarity of target and blank trial RTs and the absence of a density effect (density increases with set size in this design) would seem to argue for a global mechanism.

(3) The present result, taken with others, suggests that no single factor describes the similarity of orientations in a visual search paradigm. We have shown that categorical status and symmetry relations influence search speed. If the variety of distractor orientations is increased, still other factors become prominent; notably global structure (Moraglia, 1989) and local 'texton' gradients (Nothdurft, 1991).

In sum, apparently simple concepts like similarity, used in models of visual search, are less simple in practice than in theory. Duncan and Humphreys (1989) are, no doubt, correct in stating that search becomes easier as distractor–distractor similarity increases and more difficult as target–distractor similarity increases, but how are we to define similarity? For orientation, angular difference is not adequate even though Foster's recent data show that those differences must be part of the definition of similarity (Foster and Ward, 1991a, and b). Based on orientation difference alone, the Control condition of Experiment 1 should be *easier* than the Smaller Angle condition. The average target-distractor difference is comparable (Control: 48 deg, Smaller Angle: 44 deg) but the distractor-distractor difference is much greater in the Smaller Angle condition (Control: 48 deg; Smaller Angle: 78 deg).

The present results may be mildly distressing from the vantage point of those doing research in this field. One needs to be alert to the possibility that apparently simple stimuli are related in quite complex ways. Viewed more broadly, from the perspective of the user of the visual system, they are encouraging. They illustrate a search mechanism well suited to uncovering disruptions in textures of heterogeneous items, an ability crucial to solution of real-world search tasks.

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## NOTES

1. It might seem worth generating a Large Angle condition in which all T-D angular separations were 40 deg larger than D–D separations. However, such a condition would simply confirm that, all else being equal, search is easy if the T–D separation is greater than the D–D separation. It is the Smaller Angle condition that provides the possibility of a counter-intuitive finding.

2. Some cues to parallel search (e.g., color) are so obvious that specific instruction is superfluous. Others, like the angular separation cue described here, are more subtle. These subtle cues are not simply creations of the experimenters and their instructions. Other tasks (e.g., finding a 'T' among 'L' or a conjunction of two colors) seem quite immune to instruction.