Local and global orientation in visual search

ANDREW FOUND and HERMANN J. MÜLLER
Birkbeck College, University of London, London, England

Six experiments investigated the role of global (shape) and local (contour) orientation in visual search for an orientation target. Experiment 1 demonstrated that search for a conjunction of local contours with a distinct global orientation was less efficient than search for a target featurally distinct in terms of both global and local contour orientation. However, Experiments 2 and 4 demonstrated that the presence of a unique line contour was neither sufficient nor necessary to allow efficient search. Experiment 5 found that search for a local orientation difference was strongly impeded by irrelevant variation in global orientation, arguing for a preeminent role for global orientation. Finally, Experiment 6 demonstrated that the orientation search asymmetry holds for the global orientation of stimuli. Taken together, the results are consistent with visual search processes guided predominately by a representation of global orientation.

Over the past decade, the visual search technique has been used extensively to “probe” the representations derived in early vision. In a visual search experiment, participants are shown a display containing a variable number of items. Participants are instructed to decide whether the display contains a (usually prespecified) target item. If it does, they respond “present,” if it does not, they respond “absent.” Of particular interest is the effect that varying the total number of items in the display (set size) has on the reaction times (RTs) of the participants (embodied in the slope of the search RT by set size function). If an increase in the total number of items in the display has little or no effect on RTs, then it is assumed that the attributes that distinguish the target item from distractor items are represented in parallel across the visual field, early in visual processing. A variety of visual attributes (“features”) appear to be represented early in the visual system, including size, color, motion, stereo disparity, and, of particular relevance to the current paper, orientation.

Visual Search for Oriented Targets

Using the simplest of oriented stimuli—lines—observers can detect a target item with an orientation different from that of distractor items rapidly and in parallel, provided that the difference in orientation is sufficiently large (greater than $\approx 15^\circ$). This is consistent with a moderately coarse representation of orientation in early vision. For example, Wolfe’s (1994) Guide Search 2.0 model represents only four broad “categories” of orientation (left, right, steep, and shallow) but is capable of accurately

simulating search slopes as the orientation difference between target and distractors varies.

In common with search for other visual features, search for orientation differences exhibits an asymmetry. Search for a tilted target among vertical distractors is rapid and parallel; in contrast, search for a vertical target among tilted distractors is relatively slow, and RT increases as set size increases (provided the orientation difference is small enough, $\approx 15^\circ$). According to Treisman and Gormican (1988), this effect arises because vertical is a “prototype” orientation, with orientation coded in terms of deviation from this prototype. In this sense, search for a vertical target among tilted distractors requires search for an item that lacks a salient feature. In common with other search asymmetries, this is considered difficult.

Work by Foster and Ward (1991) suggests that the vertical and horizontal axes are particularly important in orientation coding. Foster and Ward performed detection studies in which participants searched for differently oriented line contour targets among various background (distractor) orientations. They found that threshold differences between target and distractors were lowest when the orientation of background items was either horizontal or vertical. They interpreted this pattern of results as indicating that detection of orientation in early vision is dominated by just two orthogonal filters oriented horizontally and vertically, approximately Gaussian in shape and with half-widths of about 30° at half-height. A further study (Foster, Westland, & Doherty, 1994) demonstrated that the asymmetry was still evident when the search was conducted in very sparse displays, suggesting that line detection mechanisms may be sensitive to line orientation itself rather than to local line orientation differences.

The Representation of Orientation in Early Vision

An account of orientation detection performance based of spatial filtering of the image has a number of difficulties when viewed in the context of other findings. For ex-

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ample, Bravo and Blake (1990) demonstrated that participants were able to search for groups of items that formed an oriented "emergent group." Participants searched for an emergent bar orientation target—for example, a left-tilted emergent bar (top of Figure 1)—among right-tilted emergent bars (bottom of Figure 1). No significant increase in RTs was evident as set size increased. Bravo and Blake concluded that search mechanisms can be directed toward perceptual groups that would emerge after the initial filtering of the image (see also Grossberg, Mingolla, & Ross, 1994). Importantly, the target group did not differ from distractor groups in terms of a simple featural difference; both types of emergent groups were constructed from vertical lines against a background of horizon lines (see Figure 1). Cavanagh, Arguin, and Treisman (1990) extended this finding by demonstrating that oriented bars defined in a variety of media, including texture, can be searched for efficiently.¹ Interestingly, Cavanagh et al. reported that the search asymmetry for orientation targets described above was evident for items defined in all media, suggesting that a common process underlies search for oriented items irrespective of the media they are defined in.

Additional evidence for a more complex representation of orientation in visual search than that based on the output of oriented luminance filters comes from the work of Enns and Rensink (1991). They found that participants were able to rapidly discern targets defined as configurational differences in the same line contours present in distractor items, provided that the lines were arranged such as to produce a three-dimensional (3-D) interpretation. An example is shown in Figure 2. This suggests that the global orientation of an object—at least one with a 3-D interpretation—is coded preattentively, rather than simply the orientation of individual line contours. Note that the line contours that make up the target item in Figure 2 are the same line contours (with the same orientations)

Figure 1. Schematic representation of the stimuli used by Bravo and Blake (1990). Groups of oriented line contours were arranged such that they produced an emergent oriented bar against a background of differently oriented line contours. Note that the left and right tilted bars are made up of the same line contours and, so, do not differ in terms of a simple featural line contour difference.

Figure 2. The target item (oblong oriented toward the lower right) has the same outline shape as the distractors but differs in the configuration of the internal line contours. The target item is readily visible, and search for it is relatively unaffected by the number of distractors (after Enns & Rensink, 1991).

that are present in the distractor items; they are simply arranged differently.

Orientation and Action

A representation of orientation based on global orientation makes particular sense when we consider the relevance of orientation to our interaction with objects in the real world. In order to interact with the world, the visual system must generate a detailed and continuous representation of the environment, supplying the necessary information for the motor system to execute the required response. The execution of a motor response to an object requires information concerning not only the object's location but information relevant to grasping the object, including its size, weight, and orientation. Since the motor system operates in a 3-D world, information concerning orientation must also be specified in three dimensions, taking into account the slant of an object in depth. However, we rarely pick up more than one object at a time (if ever, with any real success), and it may not be necessary for the visual system to generate a representation of global orientation for all objects in a given scene. Instead, such a representation of orientation may be derived only for the object that is the target of a motor response.

If the generation of global orientation is restricted to the target item prior to the execution of a motor response, then how is the target first located? For example, with the stimuli shown in Figure 2, there is no single unique line contour that could guide attention to the target, since it is composed of the same line contours as those of the distractor items. Perhaps the items in Figure 2 are members of a limited set of 3-D features available in parallel (Treisman & Sato, 1990). However, similar problems arise when we consider simpler stimuli that do not have a 3-D interpretation. For example, consider the search for a horizontal bar (▬) among vertical bars (|). Clearly, search would be relatively fast and near parallel; however, both the target item and the distractors are composed of four

line contours with the same orientations (two vertically oriented and two horizontally oriented). The rapidity with which the horizontal bar would be detected excludes the possibility that participants are performing a conjunction search for either a long horizontal or a short vertical line contour. One possible basis for search could be the utilization of orientation information at different spatial scales. It is widely accepted that the retinal image is processed at a number of spatial scales (Watt, 1988; Wilson & Bergen, 1984; Woodhouse & Barlow, 1982). In the case of the search for the horizontal bar among vertical bars, the orientation of these bars could be represented at a spatial scale that is sensitive to the bars' overall orientation but is relatively insensitive to the orientation of individual line contours. Thus, the presence of the horizontal bar could be determined by activity in a horizontally aligned "edge/blob" detector at the appropriate spatial scale. However, the experiments of Bravo and Blake (1990) and Cavanagh et al. (1990) described above suggest that the representation upon which orientation search operates is not directly based on the output of spatial frequency channels.

Overview of Experiments

The present experiments set out to investigate the role of the orientation of individual line contours and the global orientation of perceptual groups composed of assemblies of contours (i.e., objects) in visual search. Experiment 1 investigated whether a conjunction of line contours can be searched for efficiently when it is characterized by a clear difference in global orientation. The results of Experiment 1 were inconclusive; however, they favored an account in terms of search for a conjunction of line contours. In Experiment 2, the global orientation of items was disrupted whilst retaining the same line contours used in Experiment 1. When global orientation was disrupted, search was strongly impeded. Experiment 3 ruled out possible accounts based on spatial filtering of the stimuli at different spatial scales by specifying item boundaries as "cognitive contours" emerging at texture boundaries. Search was equally efficient when items were defined by real or cognitive contours. Experiment 4 compared search for a target item that contained a unique line contour (i.e., in terms of contours, a feature target) with search for one that did not (i.e., a contour conjunction target). However, both targets were similarly distinct from distractors in terms of global orientation. Search performance was similar for both targets, and the clear qualitative difference in search for feature and conjunction targets was not evident. Experiment 5 directly assessed the relative contributions of local contour and global shape information in search. Display items consisted of sets of either vertical or horizontal contours arranged into global bar shapes that themselves could be either horizontally or vertically oriented. Participants were instructed to discriminate either a local (contour) or a global (bar) orientation difference. A second variable was the absence or presence of task-irrelevant variation in orientation of the stimulus aspect that participants were

not required to respond to. For example, when participants were asked to determine the presence/absence of a global bar orientation difference, in one condition, the orientation of the local contours was the same (all vertical or all horizontal), and in the other bar judgment condition, the local contours were orientationally mixed (a mixture of horizontal and vertical). Participants found search for a local line contour orientation difference particularly difficult when the global bars were a mixture of vertical and horizontal orientations. This is interpreted as a more important role for global orientation in generating orientation contrast signals, which consequently strongly interfered with the detection of local contour differences. Finally, Experiment 6 demonstrated that the well-known search asymmetry for oriented items also holds for the global orientation of stimuli. Participants found the search for a vertically oriented diamond shape (constructed from contours arranged 22.5° either side of vertical) among tilted diamond distractors more difficult than search for the tilted diamond among vertical diamonds, as for simple line stimuli.

EXPERIMENT 1

Experiment 1 investigated whether a target unique in terms of global orientation can be searched for efficiently despite the fact that the individual line contours making up the stimulus were present in distractor items (i.e., in terms of line contours, the target was a conjunction of line contours). A set of diamond stimuli was used such that the target item (tilted 45° to the right) was composed of four line contours: two present in one distractor, and the other two present in the second distractor (distractors were a mixture of horizontal and vertical global orientations; see Figure 3). Additional conditions were run with only horizontal and vertical distractors present in the display (in which the target item possessed a unique line contour). A set of control conditions was also run using simple line stimuli.

Method

Participants. Six participants took part in Experiment 1. One was the principal author, 3 of the others were experienced in perceptual research but were naive as to the purpose of the experiment, and the other 2 participants were completely naive. All participants (except the principal author) in this experiment and in the subsequent experiments were paid £4 per hour for their participation. The age range of the participants was 21–32 years. All had normal or corrected vision.

Figure 3. The construction of stimuli used in Experiment 1, with line stimuli on the left and diamond stimuli in the middle. The target item is the item oriented at 45° to the right in both cases. For the diamond stimuli, the target item is composed of line contours present in the two distractors. All stimuli have the same overall length (stimuli superimposed in right of figure).

Apparatus. All stimuli in Experiment 1 and in all subsequent experiments were presented on a high-performance color CRT monitor driven by a Silicon Graphics UNIX Workstation. The laboratory was dimly illuminated to prevent reflections on the CRT. The brightness of the CRT was adjusted to a comfortable level and remained constant throughout all experiments. Responses were recorded from a four-button response box (only the leftmost and rightmost buttons were used). The participants viewed the displays from a distance of 70 cm.

Displays. The experimental stimuli consisted of two sets of items, line and diamond stimuli, made up of white lines on a black background. For each of these stimulus sets, three conditions were run that varied in terms of the distractor items present in the display. In all conditions, the target was a 45° right-tilted item (either line or diamond) present on 50% of trials. In the horizontal distractor conditions, displays contained only horizontal distractors (either lines or diamonds). In the vertical distractor conditions, displays contained only vertical distractors (either lines or diamonds). In the mixed conditions, distractors consisted of both horizontal and vertical distractors (either lines or diamonds) (see Figure 4). Antialiasing routines were used to ensure that all lines appeared smooth.

Set sizes of 9, 16, and 25 items were used with stimuli arranged in a square formation with some spatial "jittering" between items to prevent collinearity between neighboring stimuli (a random jitter of $\pm 0.25^\circ$). The overall length of the line and diamond stimuli was 0.85° ; the diamond stimuli were 0.35° wide. Overall, the displays subtended a visual angle of (on average) $4.3^\circ \times 4.3^\circ$, $5.9^\circ \times 5.9^\circ$, and $7.2^\circ \times 7.2^\circ$ for set sizes of 9, 16, and 25 items, respectively. In the mixed condition, when the set size and presence/absence of the target permitted, the number of the two distractors was equal. When the display contained an odd number of distractors, a random choice was made as to the identity of the final distractor on each trial.

Procedure. Each of the 6 participants performed a unique ordering of the three distractor conditions (horizontal, vertical, or mixed distractors). The participants retained the same ordering for both sets of stimuli. Half of the participants were tested on the line stimuli first, followed by the diamond stimuli; the other half started with the diamond stimuli. The participants were given 20–30 prac-

tice trials before starting each condition. Each condition consisted of 270 trials presented in blocks of 50 trials (the last block consisting of only 20 trials). Blocks were initiated by pressing the space bar of a keyboard positioned in front of the participants.

Each trial began with the presentation of a small fixation cross ($0.3^\circ \times 0.3^\circ$) in the center of the screen for 600 msec, after which the screen was blank for 400 msec before the display was presented. Once participants had responded, they were given visual feedback about their response in the form a large plus sign (a correct response) or a large minus sign (an incorrect response) presented on a black background. The plus sign was displayed for 1,000 msec, the minus sign was displayed for 2,000 msec to discourage errors. After feedback presentation, the screen was blank for 1,000 msec before the start of the next trial. If the participants did not respond within 3,000 msec, they were presented with the minus sign, and the trial was discarded. Only a small percentage of trials was discarded in this fashion (below 1%).

Results

Mean RTs and error rates were calculated excluding any RTs greater than 2,200 msec (less than 1% of all trials). The results for all 6 participants are shown graphically in Figure 5 for all six conditions. As would be expected for the line stimuli (top half of Figure 5) with only horizontal or vertical distractors in the display, the search functions were flat with respect to set size. When both types of distractor were present in the display (the mixed condition), the search functions remained flat; however, absent RTs were approximately 70 msec longer than RTs in the other two conditions. A different pattern of results was obtained for the diamond stimuli (lower half of Figure 5). When the distractors were either all horizontal or all vertical, the search functions were flat, as they were for the line stimuli. However, when the distractors were mixed, RTs increased with increases in set size, particularly for absent responses (consistent with serial search for the target item).

Figure 4. Example displays of the six conditions of Experiment 1. Displays are illustrated with a set size of 4 (set sizes of 9, 16, and 25 items were used in the experiment). The three conditions were horizontal, vertical, and mixed distractors for both line stimuli (top) and diamond stimuli (bottom).

Figure 5. Mean RTs and error rates for all six conditions of Experiment 1. Line stimuli conditions are shown in the top half of the figure, and diamond stimuli are shown in the bottom half, for each of the three distractor conditions (horizontal [left], vertical [middle], and mixed [right]).

A four-way analysis of variance (ANOVA) was performed on the data, with factors of stimulus type (line, diamond), distractor condition (horizontal, vertical, mixed), response (present, absent), and set size (9, 16, 25). All four main effects were significant [stimulus type, $F(1,5) = 91.11$, $p < .001$; distractor condition, $F(2,10) = 78.54$, $p < .0001$; response, $F(1,5) = 28.79$, $p < .01$; set size, $F(2,10) = 56.59$, $p < .0001$]. Overall, RTs were faster to line stimuli, RTs were longer in the mixed distractor conditions, present responses were faster than absent responses, and RTs increased with set size. Additionally, the interactions between stimulus type and distractor condition [$F(2,10) = 34.50$, $p < .0001$] between stimulus type, distractor condition, and set size [$F(4,20) = 37.30$, $p < .0001$] between stimulus type, distractor condition, and response [$F(2,10) = 20.71$, $p < .001$] and between distractor condition, response, and set size [$F(4,20) = 6.08$, $p < .01$] were significant. Thus, varying distractor composition affected RTs differentially for the two stimulus sets (lines and diamonds). To investigate these interactions further, separate three-way ANOVAs were performed for the line and diamond stimuli.

The ANOVA for line stimuli revealed that the main effects of distractor condition [$F(2,10) = 7.95$, $p < .01$] and response [$F(1,5) = 6.73$, $p < .05$] were significant, and the main effect of set size [$F(2,10) = 2.14$, $p > .1$] was

not significant. The only significant interaction was between distractor condition and response [$F(2,10) = 6.55$, $p < .05$], due to the slower absent responses in the mixed condition (a very similar pattern of results was obtained by Humphreys, Quinlan, & Riddoch, 1989, Experiment 7). The main effect of condition was presumably due to this interaction (see Figure 5). The three conditions did not differ with respect to set size. A similar analysis of the errors failed to find any difference between conditions, ruling out speed-accuracy tradeoffs.

The same analysis for the diamond stimuli revealed all three main effects to be significant [distractor condition, $F(2,10) = 58.56$, $p < .0001$; response, $F(1,5) = 44.18$, $p < .01$; set size, $F(2,10) = 39.00$, $p < .0001$]. All interactions were also significant [distractor condition $\times$ response, $F(2,10) = 58.12$, $p < .001$; distractor condition $\times$ set size, $F(4,20) = 39.22$, $p < .001$; response $\times$ set size, $F(2,10) = 6.44$, $p < .05$; distractor condition $\times$ response $\times$ set size, $F(4,20) = 4.25$, $p < .05$]. The interactions involving condition suggest that the main effect of condition was largely due to the difference between the mixed condition and the other two conditions (see Figure 5). An analysis of the errors revealed the same pattern of effects (more errors on present trials, and interactions of condition with both response and set size), which reinforces the RT differences between conditions. These RT differences are

clearly evident in the slopes of the RT by set size functions determined by linear regression (see Table 1).

The regression lines fitted to the present and absent RT set size functions (Table 1) show that five of the conditions were relatively similar in terms of intercept and slope. The mixed condition for diamond stimuli was outstanding with slopes that were larger than those in the other conditions. Whereas the slopes of the other five conditions were well within the range taken to indicate parallel search, the slopes in the mixed diamond condition were more indicative of serial search with a present to absent slope ratio close to 1:2 (although the slope values themselves were not particularly large).

Discussion

The results of Experiment 1 suggest that it is not possible to search for a target item defined in terms of global orientation. Instead, search proceeds through the detection of a unique line contour present in the target. When this strategy is not possible, because the target item does not contain a unique line contour, search reverts to a slower, more serial pattern (mixed diamond condition). The results in the mixed diamond condition are indicative of a conjunction search for the two line contours that together uniquely define the target item (see Figures 3 and 4). However, there are a number of previous findings that are not consistent with this conclusion.

For instance, Wolfe et al. (1990) examined within-dimension conjunction search for targets that were unique conjunctions of line elements present in distractor items. They presented participants with displays containing pairs of overlapping bars. Participants were required to search for a pair consisting of a vertical and obliquely tilted bar among pairs consisting of vertical and horizontal lines and horizontal and oblique bars. Participants found the task difficult with present slopes of 37 msec/item and absent slopes of 70 msec/item. Clearly, these slope values are considerably larger than those obtained for the mixed diamond condition of the present experiment. However, Wolfe et al. used lines of different luminance polarity to "weaken the overall shape cue," and this may have made the task particularly difficult.

Furthermore, Rensink and Enns (1995) have shown that the individual line contours that make up an overall stimulus configuration (in their case, a Müller-Lyer figure, such as >—<) are "preempted" by the overall stimulus. They demonstrated that search for a feature pertain-

ing to a particular line contour of the stimulus (the length of the central line contour) is difficult, relative to when the feature pertains to the overall stimulus (the overall length of the Müller-Lyer figure). This preemption effect would suggest that the attributes of the individual line contours making up the diamond stimuli are not as easily accessible to preattentive search mechanisms as the global stimulus configuration.

EXPERIMENT 2

Experiment 2 was designed to test whether the difficulty in searching for the diamond target in the mixed condition of Experiment 1 was due to the difficulty in searching for a unique conjunction of line contours that were separately present in the distractor items. The same line contours used in Experiment 1 were employed in Experiment 2; however, their arrangement was altered to produce X-shaped stimuli (see Figure 6). It was reasoned that if participants were searching for line contours (or conjunctions of line contours in the mixed diamond condition) in Experiment 1, then disruption of the global orientation of items should have little effect on search. Experiment 2 investigated whether this was the case by, in one condition, disrupting the global orientation cue without changing the orientation of the line contours employed in other conditions.

Experiment 2 consisted of three conditions. In each condition, the target item contained two line contours, one of which was present in each of the distractors (as in the mixed diamond condition of Experiment 1). The X-standard condition consisted of the same line contours used to construct the diamond stimuli in Experiment 1 rearranged to form an X shape (top of Figure 6). In the other two conditions, the stimuli contained an additional line contour placed perpendicular to the major axis of this X shape. In the X-short bar condition, this additional contour was equivalent to the width of the X-standard stimuli (i.e., the distance between the two ends of the line contours forming the X shape). Thus, the global orientations of display items in the X-short bar condition were the same as for the analogous stimuli in the X-standard condition. The X-long bar condition was similar to the X-short bar condition except that the additional bar was lengthened so that it was the same length as the other two line contours that made up the X configuration. The stimuli in the X-long bar condition no longer had a strong

Table 1
Intercepts, Slopes, and Regression Coefficients (R^2 s) for Present and Absent RTs by Set Size Functions for All Six Conditions of Experiment 1

Stimulus Type	Distractor Items	Present			Absent		
		Intercept	Slope	R^2	Intercept	Slope	R^2
Lines	Horizontal	385.6	0.82	.825	411.2	1.23	.577
	Vertical	401.7	0.66	.405	424.6	0.86	.946
	Mixed	406.6	0.89	.940	459.0	3.32	.952
Diamonds	Horizontal	409.2	-0.01	.001	425.9	1.20	.754
	Vertical	404.8	0.25	.203	453.4	-0.02	.001
	Mixed	442.2	13.16	.997	544.7	22.77	.990

Figure 6. Stimuli used in Experiment 2. Each example display contains nine items, one of which is a target item. The same line contours making up the diamond stimuli of Experiment 1 were rearranged to produce the X-standard stimuli shown at the top of the figure. The X-short bar stimuli (middle) were identical to the X-standard stimuli, except for the addition of a short bar across the major axis of the stimuli. Similarly, the X-long bar stimuli (bottom) were identical to the X-standard stimuli, except for an additional long bar.

axis along which a global orientation could be defined. It was reasoned that if search for the diamond target in the mixed condition of Experiment 1 was performed as a conjunction search for the two line contours making up the target item, then search should be relatively similar in all three conditions of Experiment 2, since the target contained the same line contours.²

Method

Participants. The same 6 participants who took part in Experiment 1 took part in Experiment 2.

Displays. Displays always contained both horizontal and vertical distractor items, the number of which was as equal as possible (see

Displays section of Experiment 1). A target was present on 50% of the trials, and, in all three conditions, it was an item tilted to the right. As in Experiment 1, displays contained 9, 16, or 25 items arranged in a square pattern with some spatial jittering in the positioning of items in the display. The size of the items and the overall size of the display was the same as in Experiment 1, except for the X-long bar stimuli, whose width (at the point of maximum extent) was 0.85°. Figure 6 contains example displays for each of the three conditions of Experiment 2.

Procedure. All 6 participants performed all three conditions. Each participant performed a unique ordering of the three conditions, with each condition performed equally often first, second, and third. The participants were given 20–30 practice trials before starting each condition. Each condition consisted of 270 trials presented in blocks, as in Experiment 1. The procedure for each trial was as in Experiment 1, except that the participants were allowed 4,000 msec to respond before being “timed out.”

Results

Mean RTs and error rates were calculated for each participant in each condition according to set size and response, excluding any RTs greater than 3,200 msec (less than 1% of all trials). The results for each condition are depicted graphically in Figure 7. The pattern of results for the X-standard and X-short bar conditions are similar in terms of both RTs and error rates. However, the X-long bar condition shows a very different pattern of results, with both RTs and errors substantially higher than in the other two conditions.

To investigate these RT differences further, a three-way ANOVA was performed with factors of condition, response, and set size. All three main effects were significant [condition, $F(2,10) = 63.81$, $p < .0001$; response, $F(1,5) = 52.49$, $p < .001$; set size, $F(2,10) = 77.87$, $p < .0001$], as were all interactions (condition $\times$ response, $F(2,10) = 39.84$, $p < .0001$; condition $\times$ set size, $F(4,20) = 33.82$, $p < .0001$; response $\times$ set size, $F(2,10) = 9.62$, $p < .01$; condition $\times$ response $\times$ set size, $F(4,20) = 5.19$, $p < .01$). Clearly, the main effect of condition was accounted for by the considerably longer responses in the X-long bar condition. The interactions between condition, response, and set size reflect the fact that RTs were not only longer in the X-long bar condition but also that absent responses were much slower than present responses and increased more as set size increased relative to in the other conditions. The errors were subjected to an identical analysis, with all three main effects again being significant [condition, $F(2,10) = 13.23$, $p < .01$; response, $F(1,5) = 10.49$, $p < .05$; set size, $F(2,10) = 15.36$, $p < .001$]. The interaction between response and set size was also significant [$F(2,10) = 12.19$, $p < .01$]. Overall error rates reinforce the pattern of differences in the RT data, with larger error rates associated with longer RTs. The differences between the X-long bar condition and the other two conditions is exemplified in the slopes and intercepts of linear regression lines fitted to the mean data, which are shown in Table 2.

Discussion

The results of the X-long bar condition demonstrate that the possession of a unique conjunction of line con-

Figure 7. Mean RTs and error rates in the three conditions of Experiment 2. The top, middle, and bottom panels show the results for the X-standard, the X-short bar, and the X-long bar conditions, respectively.

tours is not sufficient to permit efficient search for a target item. Target items in both the X-standard and the X-short bar conditions were detected relatively fast, with slopes similar to those obtained for the diamond target in the mixed distractor condition of Experiment 1. Search was much more difficult in the X-long bar condition. This is consistent with an account of search in terms of global orientation. Search was relatively easy in the X-standard

and X-short bar conditions, since the global orientation of the target in both conditions was clearly discernible from the global orientation of distractors. In contrast, search was much more difficult in the X-long bar condition, since the target had the same global orientation as distractors.

If this is the case, then how did the participants search for the target item in the X-long bar condition? Presumably, the participants had to resort to an evaluation of the line contours in the different items. In terms of line contours, the target in the X-long bar condition differed from distractors in two ways. First, it had a different conjunction of line contours from those that were present in the distractor items (as in the X-standard condition). Second, it had a unique additional line contour tilted 45° to the left. It is reasonable to assume that the most efficient means of locating the target was to search for the unique additional line rather than the unique conjunction of lines. However, since the three line contours in the X-long bar condition were all the same length, it is likely that the participants found it difficult to discriminate between the additional line contour and the other two contours, therefore making search difficult.

If the participants searched for local line contours in the X-long bar condition (since there were no global orientation differences between items), perhaps they also adopted such a strategy in the other two conditions. What results would we expect in the X-standard and X-short bar conditions if search was based on line contour differences?

In terms of line contours, we would expect search in the X-short bar condition to be easier than in the X-long bar condition. Since the additional line is shorter than the other two line contours, it will be more salient than the additional line in the X-long bar condition. However, an account of search in terms of local line contours is less convincing when we consider the X-short bar and X-standard conditions together. In terms of line contours, search in the X-short bar condition is a feature search for the short 45° tilted segment, whereas, in the X-standard condition, the target is identifiable only as a conjunction of line contours. We would expect search for the uniquely oriented short line contour in the X-short bar condition to be more efficient than search for the conjunction of line contours in the X-standard condition. In fact, mean present RTs in these two conditions were the same (X-standard, 537 msec, X-short bar, 539 msec). Although an account of search in terms of line contour orientation can explain the difficulty that the participants had in search for the target in the X-long bar condition,

Table 2
Intercepts, Slopes, and Regression Coefficients (R^2 s)
for Present and Absent RTs by Set Size Functions
for the Three Conditions of Experiment 2

Condition	Present			Absent		
	Intercept	Slope	R^2	Intercept	Slope	R^2
X-standard	393.4	8.65	.9878	400.8	18.02	.9954
X-short bar	377.6	9.69	.9986	464.9	14.73	.9848
X-long bar	547.1	26.62	1.0000	947.1	40.91	.9513

it does not account for the identical performance in the X-standard and X-short bar conditions.

In contrast, an account in terms of global orientation would predict that performance in the X-standard and X-short bar conditions would be the same (items have the same global orientations), whereas the X-long bar condition would be much more difficult (no global orientation differences between items). In the X-long bar condition, participants are "forced" to resort to scrutinizing individual line contours, because they are unable to utilize global orientation differences between items (because there are no global differences).

EXPERIMENT 3

Experiment 3 addressed an alternative account of performance in Experiments 1 and 2 in terms of the initial spatial filtering of the experimental stimuli (see introduction). To efficiently detect a range of luminance changes ("edges") that may be of ecological value, it is necessary for the visual system to filter the retinal image at a number of different spatial scales (Watt, 1988; Wilson & Bergen, 1984). It is possible that performance in previous tasks could be determined by the initial "filtering" of the stimuli. For example, differences in the global orientation of stimuli in Experiment 1 could be detected by filters sensitive to orientation at a scale sufficient to detect only the global orientation of stimuli without detecting the orientation of the local line contours. The presumably limited resolution of such filters may indeed explain why search performance was poor in the mixed diamond condition of Experiment 1, with the discrimination of signal (target) from noise (distractors) made particularly difficult by the heterogeneity of distractor items in the display. Such a filtering account would also predict that the X-long bar condition of Experiment 2 would be particularly difficult.

In Experiment 3, we tested whether the participants' performance was indeed based on information from filtering operations at a spatial scale appropriate to the extraction of global orientation. In Experiment 3, we directly tested a filtering account by providing spatial information at only one spatial scale, one that would not provide any information about the global orientation of stimuli. This was achieved by defining the outline contours of stimuli in terms of texture boundaries ("cognitive contours"). The stimuli used in the present experiment were similar to the diamond stimuli employed in Experiment 1. The control condition of Experiment 3 consisted of the diamond-shaped display items defined by white line contours on a black background (as in Experiment 1). The second, cognitive contour, condition (*cogcont* condition) employed the same items, but the outlines of the items were illusorily defined at the junction between sets of vertical (background) and horizontal (item surface) lines. The third condition (mixed condition) had the outlines of the display items defined both cognitively and by the corresponding line contours (see Figure 8). If participants are relying on information provided by spatial filtering operations to de-

tect the target, then performance should be impeded in the *cogcont* condition. However, if participants are basing search on a representation of orientation generated after the initial filtering of the image, then search performance should be similar in the three conditions.

Method

Participants. Six participants took part in Experiment 3. The age range of the participants was 21–32 years. All had normal or

Figure 8. Example displays, each containing four items, one of which is a target, for the three conditions of Experiment 3. Stimuli in the control condition (top) consisted of white line contours on a black background, stimuli in the *cogcont* condition (middle) consisted of "cognitively" defined contours, and stimuli in the mixed condition (bottom) consisted of both "cognitive" and "real" contours.

corrected vision (all except 1 participant had participated in Experiments 1 and 2).

Displays. Displays contained 4, 9, or 16 items arranged in a square pattern, with some spatial jittering in the positioning of items in the display. The target item (diamond tilted to the right) was present on 50% of the trials. Display items in Experiment 3 were twice the size of items in Experiments 1 and 2 to ensure that the cognitively defined stimulus contours would be composed of sufficient line terminations to create a strong impression of outline shape. Each item subtended a visual angle of 1.7° long $\times$ 0.7° wide. In the two conditions that involved cognitively defined contours, the vertical (background) and horizontal (figure) lines were separated by approximately 0.09° . Overall, the displays subtended, on average, $4.7^\circ \times 4.7^\circ$, $7.2^\circ \times 7.2^\circ$, and $8.3^\circ \times 8.3^\circ$ for set sizes of 4, 9, and 16 items, respectively. The spatial jittering of item position was a random amount between $\pm 0.26^\circ$ (as in Experiments 1 and 2). Figure 8 shows example displays from each of the three conditions of Experiment 3.

Procedure. All 6 participants performed all three conditions. Each participant performed a unique ordering of the three conditions. Again, each condition consisted of 270 trials presented in blocks.

Results

Mean RTs and error rates were calculated for each participant in each condition according to set size and response, excluding any RTs greater than 2,200 msec (less than 1% of all trials). The results for each of the three conditions are shown in Figure 9. As can be seen, there was little difference between the three conditions. This was borne out in an ANOVA with factors of condition, response, and set size. The main effect of condition was not significant [$F(2,10) = 0.06$, $p = .9383$], nor were any interactions involving condition. The main effects of response [$F(1,5) = 55.69$, $p < .001$] and set size [$F(2,10) = 45.16$, $p < .0001$] were significant, with absent RTs longer than present RTs, and RTs increasing as set size increased. The interaction between response and set size was also significant [$F(2,10) = 45.16$, $p < .01$], with absent RTs increasing more than present RTs as set size increased.

A similar analysis of the error data showed that the three conditions did not differ in terms of error rates [$F(2,10) = 0.17$, $p = .8423$]. The interaction between response and set size was again significant [$F(2,10) = 10.24$, $p < .01$]. Linear regressions performed on the mean data revealed that slopes for present RTs were very similar in all three conditions (control, 11.7 msec/item; cogcont, 8.5 msec/item; mixed, 10.9 msec/item).

Discussion

The results of Experiment 3 are clear: Search is equally efficient for the target items employed in the previous experiments irrespective of whether the line contours are defined by real or cognitive contours. This strongly argues against an account of search for such items by orientation-tuned spatial filters that operate at the appropriate spatial scale to respond to the overall orientation of the stimuli, while being relatively insensitive to the orientation of the individual line contours.

These results are in line with the findings of both Cavanagh et al. (1990) and Bravo and Blake (1990), who reported efficient search for orientations defined in a vari-

Figure 9. Mean RTs and error rates in the three conditions of Experiment 3. The results for the control condition are shown at the top of the figure; those for the cogcont condition, in the middle; and those for the mixed condition, at the bottom.

ety of media. However, it is important to differentiate between the Cavanagh et al. and Bravo and Blake findings and the results of the present experiment. Both of the previous studies demonstrate that search can be directed toward emergent boundaries generated by regional differences, other than luminance differences (see Grossberg, 1994; Grossberg et al., 1994). However, in both of these studies, participants searched for the orientation of

such emergent boundaries. With the present stimuli, the visual system presumably generates emergent boundaries at the junctures between the horizontal (figure) and vertical (ground) lines, and the orientation of these emergent boundaries is also coded. However, knowing the orientation of these emergent boundaries is still insufficient to determine the presence of the target item, since the emergent boundaries of the target item are also generated by distractor items. Hence, the orientation of a single contour (be it real or illusory) is not sufficient to determine the presence/absence of the target. Instead, search must be based on a representation of global orientation.

EXPERIMENT 4

The results of Experiments 1–3 strongly suggest that search for an orientation target is guided by the target's global orientation, rather than the orientation of individual line contours from which it is composed. If this is the case, then it should be possible to construct a target stimulus that is featurally distinct from distractors in terms of line contours but that is not more efficiently detected than a similar globally oriented target item that is not featurally distinct from distractor items in terms of line contours. In Experiment 4, we tested this by employing stimuli that were the same in terms of global orientation but differed in terms of the line contours they were composed of. In one condition of Experiment 4, the target item was featurally distinct in terms of line contours (z-feature) and, in the other condition, it was not (z-conjunction). In addition, two control conditions were run: lines and line-pairs conditions (see Figure 10).

Method

Participants. Eight participants took part in Experiment 4. Three participants, including the principal author, had taken part in Experiments 1–3, 1 participant had taken part only in Experiment 3, and the 4 remaining participants had not taken part in any of the previous experiments. The age range of the participants was 21–34 years. All had normal or corrected vision.

Displays. The experiment consisted of four conditions, as shown in Figure 10. In the lines condition, the stimuli were identical to the stimuli used in the mixed line condition of Experiment 1. In the line-pairs condition, the stimuli consisted of pairs of parallel lines spatially displaced against one another in the direction in which they were pointing. In the z-feature and z-conjunction conditions, these parallel lines were "joined" by a third line contour. In the z-feature condition, the orientation of this additional contour was vertical in the target item and tilted 45° to the left in the distractor items. In the z-conjunction condition, the additional line contour was also vertical in the target item and was tilted 45° to the right in the distractors. Hence, in the z-conjunction condition, the target item was not discernible from distractor items on the basis of possessing a unique line contour feature. In all conditions, the target item was present on 50% of the trials.

Set sizes of 9, 16, and 25 items were used, with items arranged as in Experiment 1. The overall length of the line stimuli was 0.85°. The other stimuli were slightly longer at 1.06° (the two parallel lines overlapped by 0.35° and were separated by 0.35°).

Procedure. All 8 participants performed all four conditions. The order in which the four conditions were performed was counterbal-

Figure 10. Target and distractor stimuli used in the four conditions of Experiment 4. The target (right-tilted) item is shown in the top right position for each of the conditions. The z-feature and z-conjunction conditions differ in the orientation of the tilted line contour present in the distractor items. In the z-feature condition, it is tilted to the left, and in the z-conjunction condition it is tilted to the right, as in the target item.

anced such that each condition was performed equally often first, second, third, and last. The participants performed either the two control conditions or the two experimental conditions first. Within these pairs of conditions, ordering was counterbalanced. Each condition consisted of 270 trials presented in blocks as in the previous experiments. The procedure for individual trials was as in Experiment 1.

Results

Group mean RT and error rates were calculated for each of the four conditions, excluding RTs greater than 2,200 msec (less than 1% of the trials). Figure 11 shows the results for both present and absent responses. Both RT and error data were subjected to a three-way ANOVA, with factors of condition, response, and set size. For RTs, all three main effects were significant [condition, $F(3,21) = 9.93, p < .01$; response, $F(1,7) = 15.31, p < .01$; set size, $F(2,14) = 22.51, p < .001$]. Absent RTs were longer than present RTs, and both absent and present RTs increased with increasing set size, particularly absent RTs [response $\times$ set size; $F(2,14) = 8.60, p < .01$]. The main effect of condition was presumably due, largely, to the difference between the z-feature and z-conjunction conditions, relative to the two control conditions. Differences between these pairs of conditions were also likely to have been responsible for the significant interactions involving condition [condition $\times$ set size, $F(6,42) = 10.30, p < .001$; condition $\times$ response, $F(3,21) = 8.57, p < .001$]. The interaction between condition and set size reflects the small increases due to set size in the control conditions, relative to larger increases in the z-feature and z-conjunction conditions. Similarly, the significant interaction between condition and response resulted from longer absent responses in the z-feature and z-conjunction conditions, relative to

Figure 11. Mean RTs and error rates for each condition of Experiment 4. The top two graphs show the results for the two control conditions (lines and line-pairs); the lower graphs show the results for the z-feature (left) and z-conjunction (right) conditions.

those in the control conditions. The analysis of the errors showed a similar pattern of differences. However, the main effect of set size ($p = .3612$) and its interaction with response ($p = .3236$) were not significant.

To “break down” the main effect of condition, the two control conditions were compared with each other, as were the z-feature and z-conjunction conditions, using separate three-way ANOVAs, with factors of condition, response, and set size. The comparison of the two control conditions revealed a significant main effect of condition [$F(1,7) = 8.94, p < .05$], due to the longer RTs in the line-pairs condition. RTs also increased more as set size increased in the line-pairs condition [condition $\times$ set size, $F(2,14) = 6.02, p < .05$].

Of particular importance is the presence/absence of differences between the z-feature and z-conjunction conditions. For RTs, the z-feature and z-conjunction conditions were, overall, not significantly different (main effect of condition, $p = .8515$). However, they did differ significantly in respect to set size [condition $\times$ set size, $F(2,14) = 5.51, p < .05$]. This reflects the somewhat steeper slopes obtained in the z-conjunction condition

relative to those in the z-feature condition (see Table 3). In contrast, the error rates were, overall, significantly different between the z-feature and z-conjunction conditions [$F(1,7) = 6.83, p < .05$], with higher error rates in the z-conjunction condition [particularly on present trials; condition $\times$ response, $F(1,7) = 9.23, p < .01$]. The interaction between condition and set size was also significant [$F(2,14) = 9.34, p < .01$], with errors increasing in the z-conjunction condition and decreasing in the z-feature condition as set size increased.

Discussion

Overall, the results suggest that the participants did, in fact, find the z-conjunction condition somewhat more difficult than the z-feature condition. Although increasing the set size increased RTs more in the z-conjunction condition, the mean present RTs in the two conditions were similar (z-conjunction, 619 msec; z-feature, 601 msec). However, this was likely to have been an underestimate of the difference, since errors on present trials were significantly higher, overall, in the z-conjunction condition (z-conjunction, 6.59%; z-feature, 3.16%). Are these dif-

Table 3
Intercepts, Slopes, and Regression Coefficients (R^2 s)
for Present and Absent RTs by Set Size Functions
for the Four Conditions of Experiment 4

Condition	Present			Absent		
	Intercept	Slope	R^2	Intercept	Slope	R^2
Lines	458.1	0.48	.874	474.9	2.29	.926
Line-pairs	504.3	0.99	.854	545.3	5.82	.985
Z-feature	556.6	2.68	.898	693.0	12.27	.999
Z-conjunction	489.6	7.81	.980	568.5	19.53	1.000

ferences indicative of different search strategies, one for a unique line contour in the z-feature condition and one for a conjunction of line contours in the z-conjunction condition? Both tasks produced slopes that were "borderline" between what is generally considered to be indicative of parallel search (present slopes less than 6 or 7 msec/item) and more serial search. This argues against the presence or absence of a single line contour guiding search to an orientation target. The results in the z-feature and z-conjunction conditions were not qualitatively different, although the fact that the participants found the z-conjunction condition more difficult suggests that local line contour orientation may be influencing search performance.

EXPERIMENT 5

The results of Experiments 1, 2, and 4 have demonstrated that the global (axial) orientation of a shape strongly influences search performance for oriented stimuli. However, the longer RTs in the mixed diamond condition of Experiment 1 and in the z-conjunction condition of Experiment 4 suggest that the orientation of local line contours also influences search. Experiment 5 attempted to directly quantify the relative importance of global and local orientation information in search, by "competing" them against each other. In one condition, the target was unique in terms of global orientation, with the local orientation of items varying randomly. In the other condition, the target was locally unique, with global orientation varying randomly. Two control conditions assessed the relative discriminability of the local and global judgments in the absence of any alternate random variation.

Theories of visual search generally differentiate between two processes that influence the deployment of attention (or guide selection): bottom-up and top-down processes. Bottom-up processes refer to aspects of the stimulus that make certain regions of a scene more salient than others (e.g., bright colors or a sudden movement). Top-down processes refer to the ability of participants to structure their attentional field to achieve a particular internal goal (e.g., utilizing a symbolic cue to direct attention to spatial locations more likely to contain a target item). Experiment 5 was concerned with the bottom-up processes known to affect search for orientation targets. Provided that a target item is sufficiently distinct, in terms of orientation, from neighboring distractors, it can be re-

sponded to rapidly even when its absolute orientation is unpredictable on a given trial. This finding has given rise to the idea that local contrast between oriented elements is computed and regions of high contrast attract attention (Nothdurft, 1991, 1992; Wolfe, 1994). Experiment 5 was designed to determine the extent to which the computation of orientation contrast is based on the global (axial) orientation of a "whole" stimulus or the local orientation of the line contours from which the global stimulus is composed.

All display items consisted of bars made up of an array of line contours (see Figure 12). The global judgments made by participants were directed to the orientation of the bar shapes; the local judgments were directed to the line contours from which the bars were composed. The global bars could be oriented either vertically or horizontally, and their component line contours could also be either horizontally or vertically oriented. Participants were required to search for an odd-one-out item: a vertical among horizontals, or vice versa. In the global control condition, participants searched for either a horizontal among vertical or a vertical among horizontal bars; on any given trial, line contours making up all of the bars were either all vertical or all horizontal. In contrast, in the local control condition, the global bar shapes were all oriented either vertically or horizontally, and a target item was a bar constructed from line contours oriented differently compared with the line contours used to construct the other bar stimuli (again, either horizontal among vertical or vertical among horizontal). In both global and local control conditions, the local and global orientation of stimuli varied randomly with respect to one another (e.g., on absent trials in the local control condition, if the line contours were all oriented vertically, then the bars were oriented either all vertically or all horizontally).

The experimental conditions were similar to the control conditions except that the stimulus attribute (global or local) that was irrelevant for the orientation judgment varied randomly among display items on a given trial. For example, in the global experimental condition, participants searched for a global bar difference (horizontal among vertical, or vice versa). However, the orientation of the line contours from which the bars were constructed was randomly either vertical or horizontal. Similarly, in the local experimental condition, the target item was composed of either horizontal or vertical contours among items constructed from vertical or horizontal contours, respectively (as in the local control condition). In addition, the global orientation of bars was randomly either horizontal or vertical.

It was reasoned that if the orientation contrast saliency map guiding bottom-up search was based on local orientation information, then variation in line contour orientation should interfere with the global bar judgments. However, if representations based on the global orientation of the bars are compared in the computation of orientation contrast, then irrelevant variation in global bar orientation should disrupt search for a local line contour target.

Figure 12. Example displays of the four conditions of Experiment 5. The two left diagrams illustrate the two global judgment conditions (searching for an odd-one-out bar); the two right diagrams are the two local judgment conditions (searching for an odd-one-out set of line contours). The two upper displays show the control conditions in which there was no variation in the alternate stimulus attribute (bar or line contour); the lower two displays show the experimental conditions in which the alternate stimulus attribute varied randomly. In each example display, the set size is 9, and a target item is present.

Method

Participants. Eight participants, including the principal author, took part in Experiment 5. Four of the 8 participants had taken part in at least two of the previous experiments; the other 4 participants had not taken part in any of the previous experiments. The age range of the participants was 21–32 years. All had normal or corrected vision.

Displays. All of the displays contained a set of bars (global attribute) composed of line contours (local attribute) presented on a background of diagonal lines. Figure 12 depicts the four conditions of Experiment 5 (see above for description). Displays contained 4, 9, or 16 bars arranged in a grid-like pattern (with some jittering in their position). On average, these displays subtended a visual angle of approximately $2.1^\circ \times 2.2^\circ$, $3.9^\circ \times 3.9^\circ$, and $5.5^\circ \times 5.5^\circ$, for set sizes of 4, 9, and 16 bars, respectively. The visual angle of each bar was $1.06^\circ \times 0.65^\circ$. The line contours making up the bars and the background were separated by 0.15° (the lines themselves were approximately 0.02° in thickness).

Procedure. All 8 participants performed all four conditions. Each condition consisted of 288 trials presented in blocks. Four of the participants performed the global judgment conditions first; the

other 4 performed the local judgment conditions first. Similarly, the order of the control and experimental conditions for both local and global judgments was counterbalanced. The participants were given 5,000 msec to respond before being “timed out.”

Results

Mean RTs and error rates were calculated, excluding any RTs longer than 3,500 msec (less than 2% of all responses). The results for all four conditions are depicted graphically in Figure 13. The upper half of Figure 13 shows the results for the global bar judgments (left) and local contour judgments (right) control conditions. The lower half of the figure shows the results of the two experimental conditions for global bar judgments (left) and local contour judgments (right). In the two control conditions, both global (bar) and local (contour) judgment RTs were very similar (the mean present RTs were 498 msec for global judgments and 519 msec for local judgment).³

However, the results were very different in the two experimental conditions, with much longer RTs for local (contour) judgments (the mean present RTs were 949 msec for local judgments and 632 msec for global judgments). These differences were investigated in a four-way ANOVA with factors of judgment (global, local), condition (control, experimental), response (present, absent), and set size (4, 9, 16).

The analysis of the RTs revealed that all four main effects and all of the interactions between main effects were significant, with the exception of the interaction between judgment and set size. To simplify the analysis, the data were averaged over the three set sizes⁴ and analyzed using a three-way ANOVA, with factors of judgment, condition, and response (the mean RTs and errors collapsed over set size are shown in Table 4).

For RTs, the three main effects were again all significant [judgment, $F(1,7) = 20.15, p < .01$; condition, $F(1,7) = 111.59, p < .0001$; response, $F(1,7) = 22.86, p < .01$]. Similarly, all interactions were significant. Importantly,

the interaction between judgment and condition was significant, with a much larger increase in local judgment RTs in the experimental condition relative to the control in comparison with global judgment RTs [$F(1,7) = 29.10, p < .01$], especially for absent responses [judgment $\times$ condition $\times$ response, $F(1,7) = 23.19, p < .01$]. The same analysis of the errors revealed only the main effects of response and condition to be significant [$F(1,7) = 63.90, p < .01$, and $F(1,7) = 17.58, p < .01$, respectively]. The interaction between judgment and condition approached significance [$F(1,7) = 4.32, p = .076$]. The results clearly demonstrate an asymmetric interaction between global and local information in detecting an orientation target in visual search. In particular, irrelevant variation in global orientation severely impeded search for a local orientation difference.

Discussion

How can this asymmetric interference between global and local orientation in visual search for an orientation

Figure 13. Mean RTs and error rates for each condition of Experiment 5. The top two graphs depict the results of the control conditions; the lower two graphs depict the results of the experimental conditions for both the global (left) and local (right) judgments.

Table 4
Mean RTs (in Milliseconds) and Errors for
Present and Absent Responses in Each of the Four Conditions
of Experiment 5 Averaged Over the Three Set Sizes

Condition	Global Judgment				Local Judgment			
	Present		Absent		Present		Absent	
	RT	Error	RT	Error	RT	Error	RT	Error
Control	498.1	5.89	509.5	1.48	518.6	6.07	524.5	2.07
Experimental	631.9	8.33	675.6	2.96	918.3	11.10	1,237.5	7.12

target be explained? Could these results be explained in terms of the processing of the display at different spatial frequencies? If the display items were presented on a plain black background, then the global bar orientations could have been detected by lower spatial frequency channels than those coding the orientation of the line contours. It is known that low-spatial-frequency information is processed more rapidly by the visual system (Watt, 1987) and could explain any effects of global precedence.⁵ However, display items were presented on background lines with the same luminance and separation as the line contours from which display items were constructed. Differential processing of information at different spatial scales is therefore unable to explain the present results. In fact, the presence of the background lines means that the global bar shapes could be reconstructed by the visual system only after the line contours and their orientations had been processed.

Although Wolfe's Guided Search model makes no distinction between global and local orientation, there are a number of possible ways in which the present results can be assessed in a "guided search" framework. One possibility is that the representation of orientation guiding search is based solely on the global orientation of items (i.e., bar orientation). However, if this were the case, then one would expect bar judgments to be unaffected by random variation in the orientation of local line contours (i.e., in the global experimental condition). However, the present RTs for global judgments were approximately 130 msec longer in the experimental condition than in the control condition. This cost can be "accommodated" if one assumes that both global and local orientation information are used to detect orientation differences (alternatively, there could be one map for global orientation and one for local orientation, which then pass activity to the master map guiding attention). Hence, the variation in local line contour orientation will generate peaks of "noisy activity" on the master map and, hence, impede search.

If we assume that both global and local orientation information influence search then why does variation in global orientation affect search much more than variation in local orientation? If global and local orientations are processed separately and their respective contrast signals passed to the master map, then it is possible that global information is "weighted" more strongly and produces larger peaks of activity on the master map. Alternatively, global information may arrive on the master map before local information. It is, at present, unclear how the Guided

Search model could be modified to account for the interactions between global and local orientation in visual search demonstrated in the present experiment.

An alternative to a Guided Search model is to account for search performance in terms of competitive grouping processes (Duncan & Humphreys, 1989). According to such an account, both local and global orientations are coded for each display item, and items group with one another on the basis of both local and global similarity. The present findings could be viewed as resulting from stronger grouping between globally similar items relative to items that are locally similar. Irrespective of differences in how search processes operate, the results of Experiment 5 demonstrate a more important role for global orientation in determining search performance.

EXPERIMENT 6

In search for orientation targets, there is a well-known asymmetry such that search for a vertical target item among distractor items tilted slightly from the vertical (say, by up to 20°) is much more difficult than search for a tilted target item among vertical distractors (see introduction). It was reasoned that, if global orientation really is the basis for search, then items should exhibit the phenomenon of search asymmetry in relation to their global orientation. To investigate this, the diamond stimuli employed in Experiment 1 were used. In the target tilted condition, the participants were instructed to search for a diamond tilted 17.5° to the right of vertical among vertical distractors. In the target vertical condition, the target was a vertical diamond among distractor diamonds tilted 17.5° to the right of vertical. As a control, the same conditions were run for line stimuli of the same length (see Figure 14).

Method

Participants. Eight participants took part in Experiment 6. Five participants (including the principal author) had taken part in previous experiments, 1 participant had taken part only in Experiment 3, and the remaining 2 participants had not taken part in any of the previous experiments. The age range of the participants was 21–32 years. All had normal or corrected vision.

Displays. The experiment consisted of four conditions in total. Two conditions consisted of diamond stimuli and two of line stimuli. These pairs of conditions differed in terms of the target item that the participants were required to search for, either tilted or vertical. In all conditions, the target item was present on 50% of the trials. In the two line conditions, the stimuli consisted of simple lines; in the diamond condition, the stimuli were composed of the diamond stimuli used in Experiment 1. In the tilted target conditions, the target was an item tilted to the right 17.5° of vertical among vertical distractors. In the vertical target conditions, the target item was vertical among distractor items tilted 17.5° to the right of vertical. Schematic example displays for each of the four conditions of Experiment 6 are shown in Figure 14. Set size, arrangement of items, and item size were the same as in Experiment 1.

Procedure. All 8 participants performed all four conditions. Half of the participants performed the two line stimuli conditions first, and the other half performed the diamond stimuli conditions first. Within these two groups, the order of conditions (either target tilted or vertical) was counterbalanced. Each condition consisted of

Figure 14. Schematic displays of the four conditions of Experiment 6. The left half of the figure shows the tilted target conditions, and the right half shows the vertical target conditions, for both line (top) and diamond stimuli (bottom). In all example displays, the set size is 9, and a target item is present.

270 trials presented in blocks. The procedure for individual trials was the same as in Experiment 1, except that the participants were given up to 4,000 msec to respond.

Results

Mean RTs and error rates were calculated, excluding any RTs longer than 3,200 msec (less than 1% of all responses). For search for the tilted line target among vertical line distractors, search was rapid and relatively unaffected by increases in set size (present slope of 2.6 msec/item; see Table 5). As in the previous experiments, search for a tilted diamond was less efficient although near parallel (present slope of 5.9 msec/item). For search for the vertical target among tilted distractors, RTs were overall much slower, with a large set size effect for absent responses. However, whereas previous studies have reported relatively large slopes when searching for the vertical item (e.g., Treisman & Gormican, 1988), the slopes for present responses in the present experiment remained flat

(4.4 msec/item for line stimuli; -1.8 msec/item for diamond stimuli).

An ANOVA of the RTs revealed that the main effect of stimulus type (lines or diamonds) was not significant [$F(1,7) = .72, p > .4$]; however, the main effect of target type (tilted or vertical) was significant [$F(1,7) = 49.68, p < .001$]. Thus, overall RTs were not different between line and diamond stimuli, but RTs in vertical target conditions were much slower than in the tilted target conditions. The main effects of response [$F(1,7) = 26.16, p < .01$] and set size [$F(2,14) = 88.43, p < .0001$] were significant, as was the interaction between the two [$F(2,14) = 21.94, p < .0001$].

The results of linear regressions performed on RT by set size functions for both present and absent responses are shown in Table 5. The small differences between stimuli (line, diamond) with respect to set size in the two target conditions were significant [stimulus $\times$ target $\times$ set size, $F(2,14) = 18.30, p < .001$]. This interaction was due to the slightly larger slopes in the tilted diamond condition relative to those in the tilted line condition (5.9 vs. 2.6 msec/item for present responses, and 10.5 vs. 3.9 msec/item for absent responses) and the smaller slopes in the vertical diamond condition relative to those in the vertical line condition (-1.8 vs. 4.4 msec/item for present responses, and 20.3 vs. 28.1 msec/item for absent responses). Although significant, this crossover in the pattern of slopes for the two stimulus types is relatively minor in relation to the actual slope differences involved. The most striking difference in the data remains the large intercept shift between search for a tilted target and search for a vertical target for both stimulus sets (lines and diamonds). The average intercept for present responses to tilted targets was around 400 msec; in contrast, the average intercept for present responses to vertical targets was approximately 750 msec.

Discussion

Search for a vertical target among tilted distractors is more difficult than search for a tilted target among vertical distractors for both line and diamond stimuli. However, the findings of the present experiment are surprising in that the pattern of results diverges from previous findings in similar tasks. For example, Treisman and Gormican (1988) reported that search for a vertical target among tilted distractors (tilted 18° to the left of vertical) yielded slopes of 28.3 msec/item for present responses and 29.6 msec/item for absent responses. This present:absent slope ratio is clearly far from the "classic"

Table 5
Intercepts, Slopes, and Regression Coefficients (R^2 s) for Present and Absent RTs
by Set Size Functions for the Four Conditions of Experiment 6

Stimuli	Condition	Present			Absent		
		Intercept	Slope	R^2	Intercept	Slope	R^2
Line	Tilted target	393.6	2.63	.9859	405.6	3.86	.9541
	Vertical target	734.9	4.37	.9873	564.3	28.12	.9900
Diamond	Tilted target	414.6	5.86	.9917	437.3	10.46	.9915
	Vertical target	774.5	-1.79	.4054	651.1	20.30	.9975

1:2 pattern taken to be indicative of serial scanning of the display. However, the cost associated with increasing the number of items in the display is clear. Why did such a pattern of results not emerge in Experiment 6?

One possibility is that the arrangement of items in the display was very different in the two studies. In Treisman and Gormican's experiment, the display items were presented within a fixed display area, and items were randomly positioned within this area. As the set size increased, items would, on average, become more closely spaced together. In the present experiment, item spacing was kept relatively constant across different set sizes. The density of display items is likely to influence search efficiency in some tasks, but how this relates to the present task is essentially an empirical question. Another possible influence on search is the semi-ordered arrangement of items in the present displays, which could have affected search in an idiosyncratic manner (see Humphreys et al., 1989). What is clear in both Treisman and Gormican's study and the present experiment is that participants find search for the vertical target much more difficult than search for a tilted target. The additional finding of Experiment 6 is that the search asymmetry for orientation targets also holds for the global (axial) orientation of search items.

GENERAL DISCUSSION

Local Versus Global Orientation in Early Vision

The experiments in the present paper have demonstrated that the relationship between an object's shape and the line contours from which it is constructed is not a straightforward one. For example, the upper part of Figure 15 shows a set of six line contours representing three different orientations. In the lower part of the figure, three possible arrangements of these six line contours are depicted. The box shape (bottom left of Figure 15) has no strong overall orientation.⁶ The bow shape in the bottom middle appears to be intrinsically more oriented than the box. However, there may still be ambiguity concerning its global orientation (presumably, most people would perceive its global orientation running from its top left to bottom right, though some may interpret it as running from its bottom left to top right, an axis through which it is also symmetrical). In contrast, the "lozenge" shape in the bottom right appears to have a relatively well-defined global axis running from its bottom left to top right. The theme of this paper has been to explore the relationship between the global orientation of shapes and the local line contours from which they are constructed. In particular, what representation of orientation is used in early vision to guide target detection/selection in visual search?

Experiment 1 compared two sets of oriented stimuli: simple lines and diamond shapes constructed from two pairs of parallel lines. In both cases, the target shape was tilted 45° to the right. For the line stimuli, the target item was responded to rapidly and in parallel irrespective of the distractors present in the display (although when

Figure 15. A set of six line contours (top of figure) can be arranged in a number of different ways to produce different shapes with different global orientations. On the lower left, the lines have been "assembled" into a square (the diagonal lines are not part of the outline shape and play no role in defining global orientation). The diagonal lines are part of the outline of the lower middle shape but are arranged perpendicular to its global axis, which runs diagonally to the left. The diagonal lines in the lower right shape are parallel to its global orientation and, to some extent, define it (they extend the shape in the direction in which they themselves are oriented).

both vertical and horizontal distractors were present, the absent response RT increased somewhat [≈ 70 msec]). For the diamond stimuli, when only horizontal or vertical distractors were present, search was also efficient and parallel.

The key condition of Experiment 1 was the mixed distractor condition for the diamond stimuli. In this condition, the target item was no longer featurally distinct in terms of its line contour composition; rather, identical line contours were present in one of the distractor items. The target item in this condition was essentially a line contour conjunction target. However, with reference to global orientation, the target item was still featurally distinct (the only right-tilted shape). If the representation of orientation in early vision is based on the global orientation of shapes, then search should have remained parallel. However, it was not parallel, favoring an account based on search for a conjunction of line contours.

Experiment 2 explored further the relationship between global shape orientation and the orientation of individual line contours. The same line contours used to generate the diamond stimuli used in Experiment 1 were reassembled to generate stimuli that were X-shaped. Experiment 2 consisted of three conditions. Stimuli in the X-standard and X-short bar conditions had clear global orientations; in contrast, stimuli in the X-long bar did not have a strong global orientation. Participants found the X-long bar condition far more difficult than the other two conditions. In terms of slope values, present RTs in the X-standard and X-short bar conditions increased by 9 msec/item; in contrast, present RTs in the X-long bar condition increased by 27 msec/item. Additionally, the mean present RTs⁷ across the three set sizes were 537, 539, and 990 msec for the X-standard, X-short bar, and X-long bar conditions, respectively. Recall that target stimuli in all conditions contained the same two line contours that formed the X shape. If search was based on de-

tecting a conjunction of line contours present in the target item in all conditions, search in the X-long bar condition should have been similarly efficient compared with search for the target in the other two conditions. Instead, the results strongly favor an account of search for the target stimuli in Experiment 2 (and, by extrapolation, those in Experiment 1) based on differences in global shape orientation. When the global shape is no longer strongly oriented, search is severely impeded.

The results of Experiment 4 confirmed the interpretation of Experiment 2—namely, that the global orientation of stimuli has a dominant influence on visual search for an orientation target. The two important conditions of Experiment 4 in this respect were the z-feature and z-conjunction conditions. Stimuli in both conditions resembled Zs: Distractors were horizontal and vertical Zs, and the target item was a Z tilted 45° to the right. The target item in the z-feature condition contained a line contour that was not present in either of the distractors. In contrast, the target item in the z-conjunction condition was composed of line contours that were all present in one or another of the distractor items. If search was based on search for line contours, then it should have been much easier to detect the target in the z-feature condition; alternatively, if search was based on the global orientation of stimuli, then search performance should have been similar in the two conditions. The results were similar, with mean present RTs of 601 and 619 msec and mean absent RTs of 897 and 893 msec for the z-feature and z-conjunction conditions, respectively. However, the two conditions did differ slightly in terms of slopes, with present slopes of approximately 3 and 8 msec/item and absent slopes of 12 and 19 msec/item for the z-feature and z-conjunction conditions, respectively. Thus, although the z-conjunction condition proved slightly more difficult, this is not the clearly discernible qualitative difference that should distinguish parallel and serial search. The participants were not relying on the presence of a particular line contour orientation to detect the target in the z-feature condition. Similarly, they were not searching for a conjunction of line contours in the z-conjunction condition. Instead, in both conditions, the participants were using the global orientation of the stimuli to direct search (although some additional contribution of the unique line contour in the z-feature condition may be improving search efficacy; see *Relating Local and Global Orientation* section below).

The results of Experiment 5 also emphasized the role of global orientation in search processes. The main finding of the experiment was that irrelevant variation in global orientation severely impeded search for a local contour difference. The cost, relative to the control condition, was an increase in mean present RTs of 430 msec. The cost associated with irrelevant local orientation when the participants made global judgments was much smaller (only 130 msec on average) for present responses. In crude terms then, the relative importance of global and local orientation information in guiding search processes is a ratio of 3.3:1.

Finally, compatible with the proposal that global orientation is the basis for search, Experiment 6 demonstrated that the well-known search asymmetry for orientation targets also holds for the global orientation of stimuli. This asymmetry has been demonstrated on numerous occasions, as far as we are aware, exclusively with simple line stimuli. For simple line stimuli, since their global and local orientations are in a one-to-one correspondence (they are just lines!), it is not possible to determine whether this asymmetry is related to their local or global orientation. The line stimuli in Experiment 6 exhibited the asymmetry: Was this because of their local contour orientations or their global shape orientations (which were the same)? However, in Experiment 6, the asymmetry was shown to hold for the global orientation of diamond stimuli. Therefore, with reference to the line stimuli, the simplest and most parsimonious account would be to view the asymmetry as an effect of their global orientation.

Processing Orientation Information at Different Spatial Scales

In order to locate a range of contours efficiently, the image must be processed at a number of different spatial scales. It is possible that filters sensitive to the overall shape of the stimuli but not sensitive to the individual line contours could provide the information upon which target presence/absence is determined. Activity in filters at the appropriate scale that are sensitive to items tilted 45° to the right of vertical but relatively insensitive to horizontal and vertical stimuli may be sufficient to detect the target item.

Experiment 3 investigated whether filtering of the display at different spatial scales might provide an account of search for a globally oriented shape by comparing search for oriented diamonds defined by illusory contours with search for diamonds defined by real contours (in a third condition, item contours were defined both by real and illusory contours). Present slope values were similar in all three conditions and were similar to results in Experiments 1 and 2 (all approximately 10 msec/item). The three conditions were also very similar to one another in terms of the overall present mean RTs. Thus, the participants were able to perform the search for a right-tilted diamond among vertical and horizontal distractors equally efficiently, regardless of whether the outline contours of the diamonds were defined by real (luminance) contours or by illusory (texture boundary) contours.

Hence, differential activation of oriented spatial filters is unable to account for the results of Experiment 3. In the condition of Experiment 3 in which item contours were defined illusorily, the only luminance contours present in the display were fine lines oriented vertically (background lines) and horizontally (foreground lines). The boundaries between these two sets of lines defined the outline shapes of the stimuli. The initial filtering of such displays will generate a great deal of activity in “fine” spatial channels that are responsive to the vertically and horizontally oriented lines. However, the out-

put of such filters will not be sufficient to determine the presence of a target item. Instead, line terminations must be grouped in some way to derive the outline contours of the diamonds. Thus, the contours of the diamonds are derived after the image has been initially filtered. If the participants were using information from spatial frequency channels to determine the target's presence, then removal of this information should impede performance. No loss in performance was observed. Hence, the participants did not rely on spatial frequency information to detect the target. If the participants were not using spatial frequency information in Experiment 3, then it seems unlikely they were using it to perform any of the other searches described in this study.

Relating Local and Global Orientation

The results for the control conditions of Experiment 4 (lines and line-pairs conditions; see Figure 10) are somewhat surprising, since no or little difference in performance would be expected between these two conditions. In fact, overall, RTs were significantly longer in the line-pairs condition than in the lines condition. Mean present RTs were 55 msec longer and mean absent RTs were 130 msec longer.⁸ Why was this the case? The two line contours that made up the stimuli in the line-pairs condition were slightly shorter than the single line contour used in the lines condition; however, both lengths were more than adequate to allow for the efficient discrimination of orientation. An alternative explanation, within the context of the present experiments, is that the line contours in the line-pair stimuli are perceptually grouped (although presumably weakly) and that some kind of representation of global orientation is derived for the pair. Unlike the line stimuli, the axial (global) orientation of the line pairs is not necessarily in a one-to-one correspondence with the orientation of the individual line contours making up each pair. For example, the top half of Figure 16 shows the target item in the line-pairs condition with three possible global axes of orientation (dotted lines) that could be imposed on the line pair by a participant. The uncertainty involved in assigning a global orientation to the line-pair stimuli may have been sufficient to slow the process of search for the target item, relative to the lines condition.

If uncertainty in assigning a global orientation to a shape is influencing search, then this might also explain the relative difficulty participants had searching for the target item in the mixed diamond condition of Experiment 1. In the conditions that employed line stimuli, there is no ambiguity in the assignment of a global orientation axis to display items. In contrast, the diamond stimuli could be assigned a number of possible global axes (see lower half of Figure 16). For example, some participants, when asked, suggested that the diamond shapes could be interpreted as squares rotated in depth. In which case, the global axis of the diamond shape could be as shown in the lower middle and right of Figure 16. This uncertainty in assigning a global axis can be construed as adding noise to the representation of global orientation. This may have been sufficient to significantly impede search based on

Figure 16. The target item of the line-pairs condition of Experiment 4 (top) and possible interpretations of its global orientation (dotted lines). The participants could have imposed a number of interpretations of global orientation on the pair of lines as shown. Similarly, ambiguity in the global axis of orientation may have affected search for the diamond stimuli (lower half of figure) employed in Experiments 1, 2, 3, and 6.

global orientation in the mixed diamond condition of Experiment 1.⁹

This leads to an interesting issue concerning the relationship between local contour and global shape orientation in Experiment 4. The two experimental conditions of Experiment 4 differed in whether the target item contained a unique line contour or whether it did not (the z-feature and z-conjunction conditions, respectively). Overall, the absence of a unique line contour in the z-conjunction target was somewhat deleterious to search. What conclusions can be drawn from this cost in the z-conjunction condition? Presumably, before global orientation of the stimuli is coded, the orientation of the component line contours of items must be coded. Figure 17 shows example target present displays for the z-feature (left) and z-conjunction (right) conditions of Experiment 4. Both diagrams show activity on three maps representing line contour orientation and three representing global shape orientation (corresponding to vertical, right-tilted, and horizontal). In the z-feature condition, the target item is the only item that generates activity on the right-tilted line contour orientation map and, so, is featurally distinct in terms of line contour information. It is also featurally distinct in terms of global orientation, since it is also the only globally right-tilted item.

In contrast, in the z-conjunction condition, all display items possess a right-tilted line contour, so all items generate activity on the right line contour map. Hence, in the z-conjunction condition, detecting the presence of the target is not simply a matter of detecting the presence of a unique line contour. Instead, sets of line contours must be grouped together, and, along with information concerning their length and relative position, a representation of their global shape orientation is derived. Figure 17 shows that the target in the z-conjunction condition is the only item that activates the right-tilted map of global orientation and, so, in terms of global orientation, it is featurally distinct.

Figure 17. Schematic models of how the processing of the displays in the z-feature (left) and z-conjunction (right) conditions of Experiment 4 in terms of local contour and global shape orientation may operate. Example displays for both conditions are shown at the top of each figure with the target item circled. The orientation of local line contours is initially represented (contour orientation maps) at the three relevant orientations (vertical, tilted 45° to the right, and horizontal). Line contours are then grouped, and a representation of global orientation is derived. Either the representation of contour orientation or that of global orientation, or both, subsequently forms the basis for visual search processes (see text). Is the advantage in search for the target in the z-feature condition because it possesses a unique line contour that can guide search? Alternatively, do stimuli in the two conditions generate different representations of global orientation that subsequently affect search?

In terms of the processing scheme presented in Figure 17, there are three possible ways in which search can be conducted: Utilizing only local contour information, utilizing both local contour and global shape information, or utilizing only global shape information. If we assume that only local contour information is used by search processes, then the targets in the z-feature and z-conjunction conditions are feature and conjunction targets, respectively. On this basis, we would expect search in the z-feature condition to be fast and parallel and in the z-conjunction condition to be slow and serial. However, despite a small slope difference, performance in the two conditions was similar. This strongly suggests that search is not based on local contour information alone; rather, global orientation is influencing search.

If both local contour and global shape orientation information is used by search processes, then target detection is somewhat more efficient in the z-feature condition because the target is, in addition to being globally unique, also unique in terms of line contour orientation. The fact that it is featurally distinct in terms of both line contour and global shape information means that it is searched

for more efficiently than the target in the z-conjunction condition, which is unique only in terms of global orientation. In terms of models of visual search, local contour and global shape orientation could be viewed as “subdimensions” of the orientation dimension.

At first sight, the results seem to suggest that both global and local orientation information are used in orientation search. However, the results are also consistent with an account of search based solely on global orientation. To derive a representation of global orientation, the local line contours in the display must be grouped, and, taking their orientation, length, and arrangement into account, a representation of global shape orientation can then be derived. We suggest that it is at this stage, *deriving global orientation*, that the difference between the z-feature and z-conjunction conditions might arise. The same set of line contours can, depending on their arrangement, produce a variety of shapes with different global orientations (see Figure 15). The processes that derive the global orientation of shapes from their component line contours must be sufficiently complex and subtle to reflect this variation in shape generated by different arrangements

of the same line contours. It is quite possible that, although relatively similar in terms of global shape, the display items in the two conditions are generating slightly different global orientations, which is sufficient to affect search somewhat deleteriously in the z-conjunction condition. Given the overall emphasis in the present discussion on the importance of global orientation information in search, we propose that the most parsimonious account of search in the z-feature and z-conjunction conditions would be one based on global orientation.

How would search mechanisms, based solely on global orientation, detect the target items in Experiment 5? Clearly, for both global judgment conditions, a representation of the global orientation of the bars will support relatively efficient target detection. However, if only global orientation information is available to search processes, then how is the presence/absence of the target determined in the local judgment conditions? One possibility is that the orientation of the local line contours making up bar items are perceived as a "surface pattern" on the bars. So, in the local judgment control condition, the target is not perceived as containing a differently oriented contour but is a bar with a different pattern. Bars can have one of two different surface patterns, depending on their orientation and the orientation of their component line contours. The line contours can be oriented either along the "length" of the bar or across the "width" of the bar (the bar itself could be oriented vertically or horizontally in both cases; see Figure 12). The participants may simply have been searching for a bar with line contours running along its length among bars with line contours running across their width, or vice versa. If the participants were using such a strategy, then this could explain why they found the local judgment experimental condition so difficult. In this condition, the display always contained bars with contours running along their length and bars with contours running along their width. Thus, the simple pattern difference that differentiated target from distractors in the local judgment control condition was no longer available to the participants. Instead, they must have had to search for a bar of a particular orientation (either vertical or horizontal) that had a different pattern to similarly oriented bars. We would expect this to be difficult, and this was borne out in the results of Experiment 5.

Conclusion

The results of the present six experiments, taken together, are consistent with visual search processes predominately driven by a representation of the global orientation of stimuli. However, this does not negate a role for local line contour orientation in some search tasks. Rather, the relationship between local and global orientation is likely to be complex, reflecting the variability in form perception itself. At present, we are conducting additional experiments to investigate this relationship further.

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NOTES

1. As well as being defined by texture, items were defined by isoluminant color differences, relative motion differences, and binocular disparity differences. In the case of binocular disparity, a significant increase in RTs was obtained as the number of display items increased, although there was no difference between present and absent slope values (both ≈ 11 msec/item).

2. In fact, in the X-short bar and X-long bar conditions, the additional line contour was a unique identifier of the target stimulus, and the participants could perform the task by simply searching for a line contour tilted 45° to the left (the target could be considered to be a feature target in terms of line contour composition). If detection is facilitated by the target possessing a unique line contour, then search might be expected to be more efficient in the X-short and X-long bar conditions than in the X-standard condition.

3. An ANOVA comparing the two control conditions revealed that, for RTs, the main effect of condition was not significant [$F(1,7) = 0.47$, $p = .51$]. However, the interaction between condition and set size was significant [$F(2,14) = 5.24$, $p < .05$], as RTs increased in the global control and decreased in the local control as set size increased (see Figure 13). An analysis of the errors failed to find any differences between the conditions.

4. The slope values for the RT/set size functions in the four conditions of Experiment 5 were all below 6.0 msec/item, except for the absent RT slopes in the global and local judgment experimental conditions (15.6 and 43.4 msec/item, respectively).

5. Navon (1977) first reported stimuli for which global attributes interfered with reports of local attributes but for which local attributes did not interfere with reports of global attributes. Subsequent studies have demonstrated a number of factors that affect precedence (e.g., size [see Kinchla & Wolfe, 1979] and sparsity of local elements [see Martin, 1979]), suggesting that precedence effects might reflect differences in discriminability of local and global attributes rather than any necessary processing sequence. However, Hughes, Layton, Baird, and Lester (1984) obtained global precedence for stimuli with global and local attributes matched in terms of discriminability (global bars made up of smaller line segments, both of which could be oriented either vertically or horizontally). Local judgments of orientation were slowed by approximately 60 msec when the global orientations were different from, compared with when they were the same as, the local orientations. More recently, Kimchi (1994) has demonstrated global interference of local nonconfigural judgments (orientation) but not of judgments concerning a configural property (closure), suggesting that configural properties were more salient to our perceptual system (however, as with previous studies, differential discriminability might offer a straightforward explanation of Kimchi's results). Despite the large number of studies ex-

ploring local/global interactions, only a few have explored local/global interactions in visual search. Saarinen (1994) contrasted search for global and local orientations (with stimuli similar to those of Hughes et al.); search for a local difference took longer than for a global difference—a finding interpreted to be in agreement with global precedence. However, Saarinen did not adequately control the discriminability of the global and local attributes. Importantly, in the present Experiment 5, the control conditions confirmed that the basic global and local discriminations were equated. In addition, Experiment 5 also addressed possible accounts of global precedence based on the earlier availability of information from low-spatial-frequency channels.

6. It could be argued that the orientation of the box is "vertical"—an assignment made in the absence of a strong global orientation (perhaps participants perceive it as resting on a surface which may confer a vertical orientation upon it). Alternatively, because we perceive this shape as a well-known geometric primitive (i.e., a square), this could confer a particular orientational interpretation upon the item. Presumably, such "culturally instantiated" interpretations (e.g., the same shape rotated 45° would be interpreted as a diamond shape, which may generate a stronger sense of global orientation) are relatively weak in contrast to the physical constraints imposed by an object's shape.

7. The mean present RTs were compared because we consider intercept values to be too "slope sensitive" (i.e., long RTs can generate small intercept values if the slope is large). If the slope value in a given experiment is very large, then the intercept value could, in theory, be negative. The possibility of negative intercept values underlines the limited explanatory worth of intercept measures.

8. Mean present RTs (with the data averaged over different set sizes) were 466 msec in the lines condition and 521 msec in the line-pairs condition. For absent responses, mean RTs were 512 msec in the lines condition and 642 msec in the line-pairs condition.

9. Another factor that may have contributed to the comparative difficulty of target detection in the mixed diamond condition is the apparent length difference between the line and diamond stimuli employed in Experiment 1. The diamond stimuli appeared to be shorter in length than the line stimuli, although they were actually the same length. To determine whether there was a genuine perceptual shortening of the diamond stimuli relative to the line stimuli, 8 participants (some of whom had taken part in the present experiments) were asked to categorize comparison lines as either longer or shorter than a standard diamond shape (as used in Experiments 1, 2, 3, and 6). The diamond shape was always the same length (3 cm); however, the length of the lines participants had to rate was variable (between 2.0 and 3.2 cm). The percentage of shorter responses for each comparison line length was determined and plotted. The 50% level was determined as 2.52 cm. This value represents an apparent shortening of the diamond stimulus, relative to simple line stimuli, of approximately 15%.

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