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Roles of Salience and Strategy in Conjunction Search

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In some cases, the search for a conjunction target proceeds through the smaller group of elements in a display, whereas in others, search is limited to those elements that share a particular feature with the target. In 6 experiments, participants searched for a conjunction target among displays consisting of various proportions of 2 distractor types. Smaller-group search was more prevalent than target-feature search with denser displays and with features that were highly discriminable. Explicit instructions to limit search to a specific feature affected performance only when the discriminability of the guiding feature was much greater than the other target feature. Together, these experiments show that bottom-up factors have more influence in guiding conjunction searches than previously thought.

Much of everyday life consists of visual search tasks, like when you hope to pick your own car out from among an unending sea of others in the parking lot. Whereas your car might have the same color as some cars and the same shape as others, its particular combination of features is unique. How then might you most efficiently locate what you seek? A long succession of search experiments (see Wolfe, 1998, for a review) has shown that searches for targets defined by a conjunction of features are generally more difficult than searches in which the target is defined by a single feature and generally less difficult than searches in which the target and distractors are all different spatial arrangements of the same basic components (such as a search for a *T* among *L*s). The fact that conjunction searches are intermediate in difficulty suggests that they make heavy demands on mechanisms for guiding search but that they are not so demanding that the guidance is completely ineffective. Thus, understanding conjunction searches could be key to understanding the search mechanisms that guide visual attention.

The commonly observed distinction between the response time (RT) patterns of feature searches and conjunction searches has been offered as evidence that visual information is processed in two successive stages. According to these models, an initial preattentive stage registers the presence of primitive features at each location across the entire visual field all at once. The results of this stage are passed along to a subsequent attentive stage that can perform more complex discriminations, but only by focusing on one location in the visual field at a time and moving serially between locations. Most of the work for feature searches can be done preattentively, yielding RTs that are relatively immune to increases in display size. Because conjunction searches require the focused attention provided by the serial attentive mechanism, RTs for many conjunction searches rise with increases in display size (Cave & Wolfe, 1990; Hoffman, 1979; Neisser, 1967; Treisman & Gelade, 1980), although some authors have questioned the preattentive–attentive dichotomy (e.g., Carrasco & Yeshurun, 1998; Cheal & Lyon, 1992; Joseph, Chun, & Nakayama, 1997; Kinchla, 1992; McElree & Carrasco, 1999; Palmer, 1995).

The serial search account is not the only way to explain performance in conjunction searches. Townsend (1990) showed that a distinction between flat RT functions and steep RT functions can be explained by a limited-capacity parallel mechanism. Although Townsend's criticism is certainly apt, the conclusions drawn here rely upon the assumption that greater demands upon the attentional stage give rise to increasing RTs and not upon any assumption about whether the underlying attentional mechanism operates serially or in parallel. Another account of visual search is designed to explain search performance without invoking any attentional effects whatsoever (Eckstein, Thomas, Palmer, & Shimozaki, 2000; Palmer, 1998; Palmer, Verghese, & Pavel, 2000). We expect that the signal detection issues raised in these studies will play an important role in accounting for visual search but that it will not be possible to account for all aspects of search without invoking attention.

Many current attention theories claim that the output of the preattentive stage eliminates some elements from attentional search by guiding the second stage to the locations that are likely to contain the target (Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989). For example, in a search for a target defined by a conjunction of color and orientation, information from the preattentive stage can guide search toward the objects that share the target's color or the objects that share the target's orientation.

There are two different ways in which a preattentive mechanism can guide attention to the elements most likely to be a target, and they are illustrated in the two subsystems within the Guided Search model (Cave & Wolfe, 1990). First, if the features defining the target are known, then objects or locations with those features can

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be favored over those with other features. In the Guided Search model, the mechanism providing this type of guidance is described as top down, because the target features are specified by signals coming down to the preattentive mechanism from higher level systems. Information from different feature dimensions can be used simultaneously to guide search, but, nevertheless, most of the selected elements will often be from one distractor type. We label this type of search as *target-feature search*.

The second method for guiding search relies on differences within the stimulus and is independent of the features that define the target. Because it is driven by the stimulus, this mechanism in the Guided Search model has been labeled bottom up, and it favors those locations with a feature that differs from other features in the display. When a search display has fewer members of one distractor type than of the other, the bottom-up system will guide attention to members of the smaller group. Although searching through the smaller of two distractor groups (herein referred to as *smaller-group search*) seems to be driven mainly by bottom-up salience, some have claimed that it is primarily a consequence of a top-down strategy (see, e.g., Poisson & Wilkinson, 1992; Zohary & Hochstein, 1989).

Unequal Distractor Set Sizes

Egeth, Virzi, and Garbart (1984) noted that when each type of distractor is equally represented in the visual field—as in the traditional visual search paradigm—the total number of distractors is perfectly confounded with the number of either type of distractor. Thus, although RTs that increase with display size are consistent with effortful search through the entire display, such results are also consistent with search through just one set of distractors. Egeth et al. sought to distinguish between these two hypotheses by varying the numbers of one distractor type independently of the other. In the unconfounded condition, participants determined whether a red *O* target was present among a fixed number of red *N* distractors and a variable number of black *O* distractors. In the confounded condition, displays contained equal numbers of red *N*s and black *O*s. In both conditions, the experimenters instructed participants to try to restrict their search to just the red elements. RTs in the unconfounded condition were relatively flat functions of display size, suggesting that participants were indeed able to restrict their search as instructed. In the confounded condition, the slopes of RT functions were similar to those from previous conjunction search experiments (Treisman, Sykes, & Gelade, 1977). From this similarity between the performance of their own instructed participants and Treisman et al.'s uninstructed participants, Egeth et al. speculated that participants performing conjunction searches may automatically restrict their search to a single set of distractors, even when not so instructed.

Although it is plausible that Egeth et al.'s (1984) participants relied on target-feature search in accordance with the experimenters' instructions, an alternative explanation is that they searched through the smaller and thus more salient group of distractors. Cave and Wolfe (1990) used a simulation of visual search to demonstrate that the shallow slopes in Egeth et al.'s unconfounded condition could have been attributable to bottom-up salience, rather than top-down strategy. In the unconfounded condition, each member of the smaller group had more neighbors with different features than any member of the larger group, due simply to the disparity between the groups' sizes. Because the bottom-up activation given to each location in the Guided Search model is proportional to the difference between that location's features and the features at other locations, a red object among a field containing a majority of black objects would receive more bottom-up activation than any of the locations containing black objects. No such bottom-up benefit would accrue to any locations in the confounded condition. Although Egeth et al.'s data show that conjunction search can be limited to a subset of elements, it is impossible to determine from their data whether the restriction of search was primarily a consequence of a top-down strategy or bottom-up salience.

Smaller-Group Search

Early evidence for smaller-group search came from a study by Zohary and Hochstein (1989). In their study, participants searched for a red horizontal target from among a field of 64 objects consisting of between 0 and 64 red vertical items, with the remainder of the field consisting of green horizontal items. The asynchrony between the onset of the stimulus and the onset of a mask was adjusted until participants were able to correctly determine in 70% of the trials whether a target was present. A plot of the stimulus onset asynchrony at 70% criterion as a function of the number of green objects in the display revealed an inverted-U shape. Target detection was most efficient when one distractor type predominated, becoming less efficient as the distractor set sizes tended toward equality, then becoming more efficient as the other distractor type predominated. Later experiments showed that these conclusions could be extended to reaction time (Poisson & Wilkinson, 1992) and eye movement (Shen, Reingold, & Pomplun, 2000) paradigms.

Zohary and Hochstein (1989) interpreted their inverted U as suggesting that participants preattentively grouped the distractors along two feature dimensions, then restricted their search to the smaller of the two groups—either the group with the target's color or the group with the target's orientation. Although their data are indeed consistent with a preattentive grouping followed by a high-level group selection, they are also consistent with a simpler process in which attention is guided to elements in the smaller group by the salience of their features. This possibility is illustrated in the FeatureGate (Cave, 1999; Cave, Kim, Bichot & Sobel, 2002) model of visual attention. In FeatureGate—as in Guided Search, the model out of which it grew—each object in the visual field receives a top-down activation in proportion to its similarity to a target and a bottom-up activation in proportion to the dissimilarity between that object's features and the features of objects in neighboring locations. Because bottom-up activations are calculated in this fashion, they tend to rise along with increases in display density (as in Bravo & Nakayama, 1992). FeatureGate selects a single location in the visual field by carrying out competitions at each level in a hierarchy of maps. Objects that have a high activation relative to their neighbors pass their features upward from one level in the hierarchy to the next. Once a set of features from a single location reaches the uppermost level, they are compared with a set of target features to determine whether the target has been found or further search cycles should be carried out. In a visual field containing a small number of one type of distractor and a larger number of another type of distractor, each member of the smaller group is more likely to be adjacent to more of the opposite type of distractor than any member of the larger group. FeatureGate will therefore generally assign larger bottom-up activations to smaller-group members than to larger-group members. As depicted in Figure 1, FeatureGate can produce an inverted-U pattern as a function of distractor ratio, similar to that found by Zohary and Hochstein. FeatureGate accomplishes this smaller-group search without first segregating the visual field into two groups (see also Wolfe, 1994).

In FeatureGate, smaller-group search depends entirely on the bottom-up system, which is driven by feature differences in the stimulus array. It requires only local comparisons between nearby objects and generally leads to quick and efficient selection of those stimulus elements belonging to the smaller group. In contrast, the method proposed by Zohary and Hochstein (1989) requires that the distractors first be organized into two groups and that the sizes of the groups be compared. Then, the smaller group must somehow be selected and the larger group inhibited, perhaps by identifying the target feature present in the smaller group (color or orientation) and passing that information to a top-down attention system that activates all objects with that feature. The method of grouping and comparing sizes is certainly plausible, but the method of bottom-up feature comparisons is relatively simpler.

Target-Feature Search

Whereas the previous studies support the claim that search can be limited to the smaller group of distractors, subsequent experiments showed that search can also be limited to the group of distractors sharing a particular feature with the target. Kaptein, Theeuwes, and van der Heijden (1995) sought to isolate goal-driven search from stimulus-driven salience effects. In their experiments, participants were instructed to search for a red vertical line segment and—in three out of four experiments—to limit their search to the red objects. Distractors were green vertical line segments and red line segments tilted just 20° clockwise from vertical. RTs rose monotonically with the number of items with the target's color but remained constant across increasing numbers of items with the nontarget color. The authors concluded that participants preattentively segregated the set of red items from the rest of the display, then searched through just the red items until the one vertical item was located. Further, they claimed that searching through just the red items was a top-down, goal-driven process, rather than a bottom-up, salience-driven process. That is, if participants had restricted their search to the more salient group of objects, they would have searched through the smaller set (vertical items) when red items predominated. However, this argument rests on the assumption that the smaller group was always salient enough to draw attention effectively. In this experiment, the small differences in orientation (0° vs. 20°) may have made it difficult to select vertical items and exclude tilted distractors. Participants may have fallen back on a top-down target-color search only because the subtle orientation differences made a bottom-up smaller-group search ineffective.

In a later study, Bacon and Egeth (1997) elicited target-feature search when both of the target's features were easily discriminable. In the first of two experiments, participants searched for a red horizontal line segment among red vertical and green horizontal distractors. One group of participants was told to restrict their search to the red items; the other group was told to restrict their search to the horizontal items. Stimulus sets were constructed to match these instructions so that, for example, participants instructed to search through the red items saw more displays in which green items predominated. RTs rose along with the set of items mentioned in the instructions, leading Bacon and Egeth to conclude that participants responded to the instructions by exerting top-down control to restrict their search to a particular feature-defined subset of objects. However, the top-down control might have been triggered by the distribution of distractor types in the series of stimuli rather than by goals established in response to the instructions.

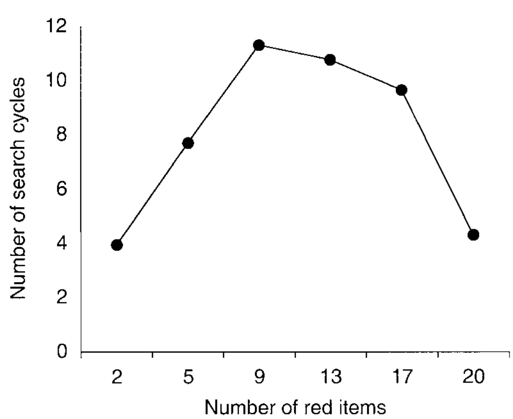

Figure 1. FeatureGate's response time (in cycles) for conjunction searches in which the total number of distractors is held constant at 20. Search is fastest when the ratio of one distractor to the other is most lopsided, that is, 1 red vertical distractor to 19 green horizontal distractors or 19 red vertical distractors to 1 green horizontal distractor. Search cycles increase as the distractor set becomes more evenly divided between the two. Each data point is the mean number of search cycles across 100 iterations of random display configurations.

Experimental Testing of Smaller-Group Search Versus Target-Feature Search

Previous studies have left open important questions about how search is guided when the target is a conjunction of features. Egeth, Virzi, and Garbart's (1984) results could reflect either smaller-group search or target-feature search. Smaller-group search seems more likely because of its efficiency, but two studies (Bacon & Egeth, 1997; Kaptein et al., 1995) suggest that participants can adopt a goal of searching for a particular feature and that this goal then governs visual search. In both cases, however, there is an alternative explanation. In Experiments 1 and 4, we compare searches for a target with salient defining features against those in which the salience of one feature has been reduced, and in Experiment 2, we investigate the influence of explicit instructions. Furthermore, because different results across studies may have been due in part to the disparate number of search elements in the displays, in Experiments 5 and 6, we use displays with different set sizes. In the studies described above, eye movements were usually prevented by limiting the exposure time. This procedure allows conclusions to be drawn specifically about the nature of covert attention, but it may also interfere with search behavior in unintended ways. In this study, we examine the influence of brief exposure on search behavior by comparing the results between search tasks in which exposure duration is unlimited and those in which exposure duration is brief (Experiments 1 and 3). In addition to exploring the balance between smaller-group search and target-feature search, these experiments also shed new light on the contributions of bottom-up and top-down attentional systems to conjunction search.

Together the results from these experiments show that the attentional system is remarkably flexible in responding to different situations. Its methods generally allow targets to be found efficiently despite the unpredictability of the environment and the difficulty in discriminating some feature. Nonetheless, it can adjust the search method using top-down information from instructions for better results.

Experiment 1: Orientation Differences

In the experiments of Kaptein et al. (1995), the target's orientation diverged from the distractors' orientation by just 20°, and participants limited their search to the group sharing the target's color. Why did they restrict their search to the group with the target's color? To determine whether it was the similar orientations that led participants to search through the group with the target's color, in Experiment 1 we manipulated the difference between the target's and distractors' orientations.

Method

Participants. A total of 24 Vanderbilt University undergraduate students volunteered for the experiment to partially fulfill the requirements of an introductory psychology class. All participants had normal or corrected-to-normal vision and reported having no color vision deficits.

Apparatus. The experiment was conducted on Macintosh IIsi microcomputers running AppleColor monitors, each with a screen resolution of 640 × 480 pixels. The stimulus colors were matched across different monitors for chromaticity and brightness by a Minolta cathode ray tube color analyzer. Responses were collected by means of custom-built button boxes connected to Strawberry Tree parallel interface cards. Clocks on the interface cards timed the responses. Chin rests ensured a constant viewing distance of 56 cm.

Stimuli. Stimulus displays consisted of 11 line segments evenly distributed on an imaginary circle with a diameter of about 6.5° of visual angle against a white background. Each individual line segment was 1.4° long × 0.36° wide. At the center of the circle was a black fixation cross consisting of two perpendicular intersecting line segments that were each 0.65° long. A red vertical line segment (the target) was present in half the trials (Commission Internationale de l'Eclairage [CIE] *x/y* coordinates of .61/.33, with a luminance of 16 cd/m^2). In the *distinct-orientations condition,* the distractors consisted of green (.28/.57, 25 cd/m^2) vertical and red horizontal line segments, whereas in the *similar-orientations condition,* the distractors consisted of green vertical line segments and red line segments tilted 20° clockwise from vertical. Figure 2A depicts an example of the displays from each condition. Although the total number of objects (target plus both types of distractor) remained constant at 11, the relative contribution of each type of distractor varied across trials. In target trials, each display was equally likely to contain 1, 3, 5, 7, or 9 of one type of distractor with 9, 7, 5, 3, or 1 of the other type of distractor. In blank trials, the number of distractors in the larger group was increased by 1 in order to replace the target; when the two distractor sets were equally sized, the type of distractor replacing the target was determined randomly.

Procedure. The participants were evenly and randomly divided between the distinct-orientations condition and the similar-orientations condition. Participants were instructed to search for a red vertical line segment and to indicate whether the target was present or absent by pressing a button with the index or middle finger, respectively, of their dominant hand, and to respond as quickly as possible without making mistakes. A tone was sounded immediately following any mistaken responses. Each trial began with the presentation of the fixation cross, followed 750 ms later by the stimulus display that remained visible until one of the buttons was depressed. The time between the stimulus onset and the response was measured to the nearest millisecond by a clock on the interface card. Following the response was an interval of 750 ms until the onset of the fixation cross for the following trial. The experiment began with a practice block of 20 trials followed by eight test blocks. Each test block of 110 trials contained every combination of target presence (2), distractor mixture (5), and target location (11) presented in random order. In this experiment and in all subsequent experiments, participants were encouraged to take breaks between test blocks.

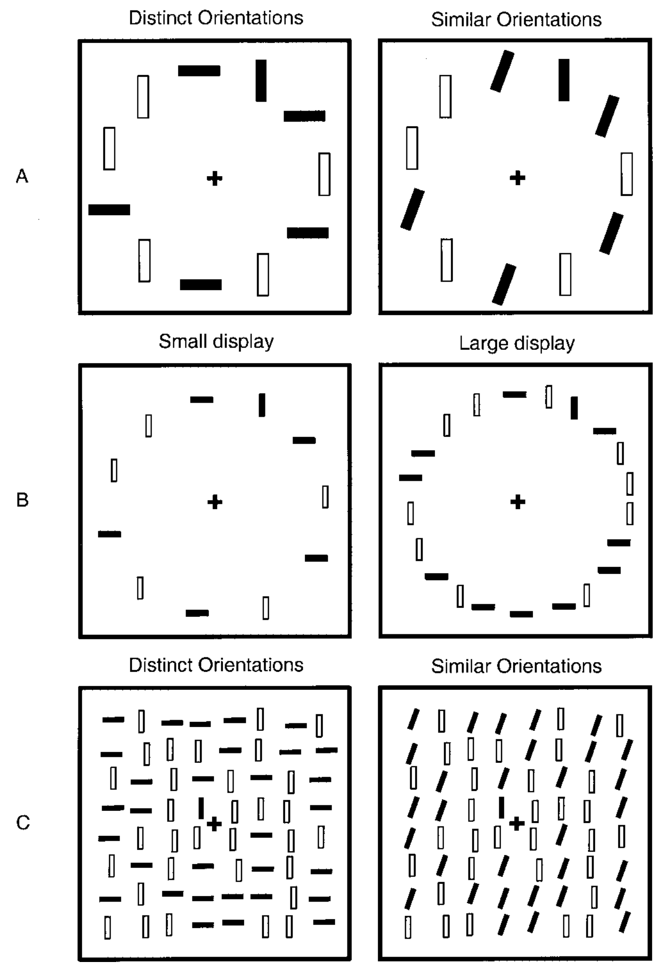

Figure 2. Examples of stimuli for Experiments 1–3 (A), Experiment 5 (B), and Experiment 6 (C). Filled rectangles represent red objects, and unfilled rectangles represent green objects. The fixation cross was black.

Results and Discussion

For each participant and at each combination of target presence and distractor ratio, we iteratively trimmed data points that fell more than three standard deviations above or below the cell mean, removing 4.5% of the total data points from analysis. Figure 3 depicts RTs and error rates as a function of distractor ratio. The five levels of distractor ratio are expressed in terms of the number of red distractors. When the number of red distractors was high, the number of green distractors was low, and vice versa.

RTs were submitted to a three-way analysis of variance (ANOVA) with target presence and distractor ratio as within-subject variables and distractor orientation as a between-subjects variable. There were main effects of distractor ratio, $F(4, 88) = 43.9$, $p < .01$; and distractor orientation, $F(1, 22) = 4.41$, $p < .05$. The Target Presence × Distractor Ratio interaction, $F(4, 88) = 17.6$, $p < .01$, and the Distractor Ratio × Distractor Orientation interaction, $F(4, 88) = 10.3$, $p < .01$, were also significant.

Although the interactions indicate that RT functions of distractor ratio differed between the two levels of target presence and the two distractor orientation conditions, planned contrasts were calculated to locate specific trends. Figure 4 depicts several hypothetical patterns of RT as a function of the number of red items. To determine which type of search predominates in any given condition, we used the same diagnostic as did Bacon and Egeth (1997). If search is restricted to the smaller group, response latency should be at a minimum when one of the groups is much smaller than the other, rising to a maximum when the two groups are equal in size, then falling again to the point at which the second group is much smaller than the first. If search is restricted to the subset of objects that share a particular feature with the target, RT should increase along with the size of the group with that feature. Thus, the presence of a quadratic trend in RT should accompany smaller-group search, and a linear trend should accompany target-feature search. It is also possible that some combination of the two methods can be pursued simultaneously, especially if the effects of bottom-up and top-down systems are combined as in the Guided Search and FeatureGate models. Thus, the linear and quadratic trends could both be significant. In target trials, the similar-orientations condition had both the linear trend, $F(1, 176) = 42.7$, $p < .01$, and the quadratic trend, $F(1, 176) = 17.8$, $p < .01$; but in the distinct-orientations condition, only the quadratic trend was significant, $F(1, 176) = 8.33$, $p < .01$. The linear trend in the similar-orientations/target condition indicates that RTs rose along with the number of red items and shows that search proceeded through the items sharing the target's color.

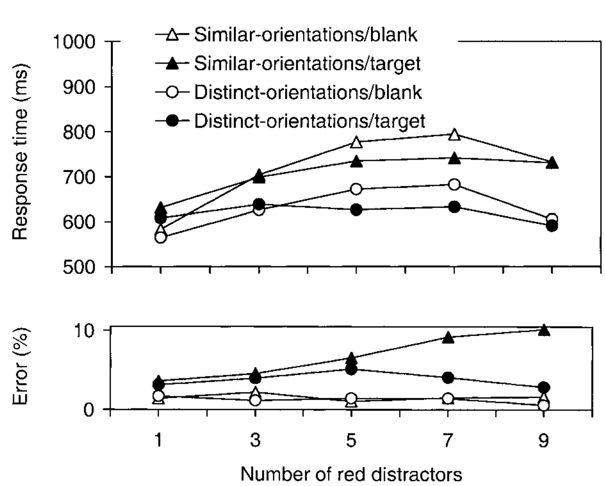

Figure 3. Mean response times (top) and error rates (bottom) in Experiment 1 as a function of distractor ratio, expressed as the number of red distractors in the display.

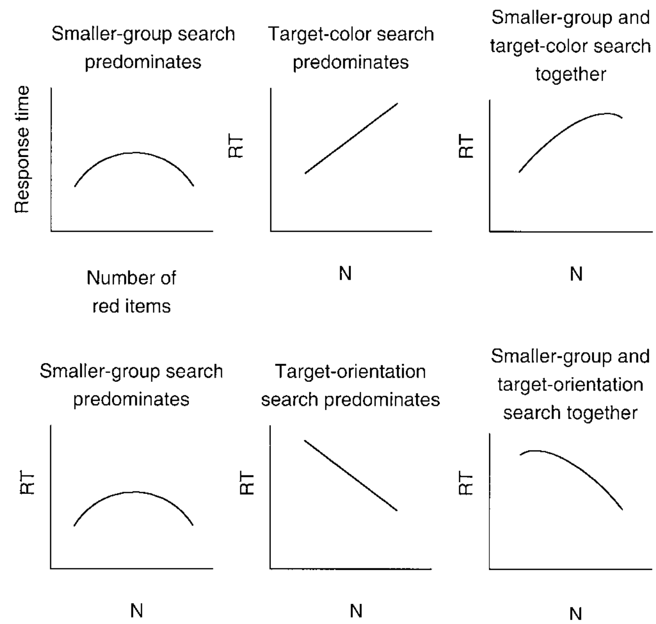

Figure 4. Hypothetical patterns of response time (RT) as a function of number of red items (N). From "Goal-Directed Guidance of Attention: Evidence From Conjunctive Visual Search," by W. F. Bacon and H. E. Egeth, 1997, *Journal of Experimental Psychology: Human Perception and Performance, 23,* p. 952. Copyright 1997 by the American Psychological Association. Adapted with permission of the author.

An additional set of planned contrasts comparing trends across different conditions revealed a stronger linear trend in the similar-orientations/target condition than in the distinct-orientations/target condition, $F(1, 176) = 29.0$, $p < .01$, and a stronger linear trend in the similar-orientations/blank than the distinct-orientations/blank condition, $F(1, 176) = 22.9$, $p < .01$. RTs rose more steeply with the number of red items in the similar-orientations condition than in the distinct-orientations condition, regardless of whether the target was present.

These results show that participants rely on some combination of smaller-group and target-feature search and that the degree to which one search method is used over the other depends on the stimulus conditions. When the difference between orientations was large, participants were able to search through whichever group happened to be smaller. When orientation differences were small, participants tended to search through the group sharing the target's color, even though they had not been instructed to do so.

In both the similar- and distinct-orientations conditions, RTs rose more steeply and had a more prominent quadratic component when the target was absent than when it was present; in the similar conditions: linear trend, $F(1, 88) = 12.3$, $p < .01$; and quadratic trend, $F(1, 88) = 22.8$, $p < .01$; in the distinct-orientations conditions: linear trend, $F(1, 88) = 18.1$, $p < .01$; and quadratic trend, $F(1, 88) = 14.2$, $p < .01$. In blank trials, participants attended more to the target's color than in target trials, and the longest searches occurred when the display was not dominated by one type of distractor.

Interpreting RTs for blank trials is tricky (Cave & Wolfe, 1990; Chun & Wolfe, 1996). When considered in relation to these models, the stronger quadratic effect in the blank trials suggests that distractor activations were much higher when the display contained roughly equal numbers of both types of distractor. This conclusion fits with the Guided Search model and other models in which bottom-up activation increases with the variation across distractors.

The stronger linear trend in the blank trials indicates that target-color distractors generally have higher activations than target-orientation distractors. This bias toward the group sharing the target's color in blank trials was also evident in the experiments of Zohary and Hochstein (1989) and Poisson and Wilkinson (1992), as well as the third experiment in Chun and Wolfe (1996). On the basis of this evidence, Bacon and Egeth (1997) suggested that grouping by color is more efficient than by orientation. An alternative explanation may be that the difference between the target's and distractors' colors was more salient than the difference between orientations and that we tend to group along the more salient feature dimension. Experiment 4, in which the difference between the target's and distractors' colors is manipulated, will have some bearing on this issue.

Error rates were submitted to a three-way ANOVA, revealing main effects of target presence, $F(1, 22) = 27.0$, $p < .01$; and distractor ratio, $F(4, 88) = 3.43$, $p < .05$. Just as in the RT analysis, the Target Presence $\times$ Distractor Ratio interaction, $F(4, 88) = 6.63$, $p < .01$, and Distractor Ratio $\times$ Distractor Orientation interaction, $F(4, 88) = 6.06$, $p < .01$, were also significant. As can be seen in the bottom part of Figure 3, the mean error rates were higher in target than blank trials, which is not surprising, because misses are generally more common than false alarms in visual search experiments. Also, mean error rates in blank trials were relatively flat across all levels of distractor ratio; in target trials, mean error rate patterns resembled the RT patterns in their respective conditions, suggesting that there was no speed–accuracy trade-off. However, in the similar-orientations/target condition between the points representing seven and nine red distractors, RTs decreased as error rates increased. If this reflects a speed–accuracy trade-off, it does not affect the conclusions we draw from this experiment. Our hypothesis was that in the similar-orientations conditions, participants would search through the red elements, which would lead to a stronger linear trend than in the distinct-orientations condition. That is, the speed–accuracy trade-off represents a bias against our hypothesis that small differences in one feature encourage searches through the group with the other target feature so we can safely conclude that any data in support of our hypothesis could not be attributable to the bias.

To be certain that eliminating the speed–accuracy trade-off would result in a stronger linear trend, we tested 5 more participants in the similar-orientations condition and gave them new instructions intended to reduce the number of misses. That is, we instructed them to wait until they were certain that no target was present before answering *no*. Mean error rates never exceeded 3.5% and resembled the RT data across all distractor ratios. RTs decreased between the target trials with seven red items and nine red items, as in the original experiment. However, the overall RT function across all distractor ratios showed a much steeper increase with the number of red items than in the data from the original participants. If the participants in the original experiment had performed the experiment more carefully, the linear trend in the similar-orientations condition would have been as strong as or stronger than what was obtained.

Experiment 2: Explicit Instructions

In Egeth et al. (1984) and the first experiment of Bacon and Egeth (1997), the experimenters instructed participants to restrict their search to the items sharing a particular feature with the target; the resulting linear trends of RTs suggested that the participants were following the experimenters' instructions. Note, however, that the group mentioned in the instructions was generally the smaller group, and when neither group predominated, as in Bacon and Egeth's second experiment, participants did not heed instructions. Also, in the first three of four experiments by Kaptein et al. (1995), participants were instructed to limit their search to a particular group, and, here again, the RT functions suggested that participants were following instructions. However, in these experiments, the group mentioned in the instructions was the one defined by the more salient of the target's features. In Kaptein et al.'s fourth experiment, participants were not instructed to limit their search to any particular group, but the results showed that they searched through the group with the target's color, just as in the previous three experiments. Although the combined results from these three studies suggest that participants concocted their own method of search without regard to the experimenters' instructions, there has been no experimental manipulation of instructions—holding all other factors constant—to test this conclusion. In Experiment 2, participants were instructed to limit their search to the group of items sharing the target's color. Comparing the results from Experiment 2 with those from Experiment 1 should reveal the effect of instructions on search behavior when the group mentioned in the instructions is defined by the more salient feature (as in the similar-orientations condition of Experiment 1) and when it is not (as in the distinct-orientations condition of Experiment 1).

Method

Participants. A total of 24 participants similar to those described in Experiment 1 were tested. No participants served in both experiments.

Apparatus and stimuli. The apparatus and stimuli in Experiment 2 were the same as in the previous experiment.

Procedure. The procedure in Experiment 2 was the same as in the previous experiment, with one exception. As well as the instructions that had been given to participants in Experiment 1, participants in Experiment 2 were also instructed to search through the group of items with the target's color and to ignore the items that did not have the target's color.

Results and Discussion

The same trimming procedure used in Experiment 1 excluded 4.5% of the total data points from analysis. RTs and mean error rates are plotted in Figure 5. As in Experiment 1, mean error rates in blank trials were low and relatively flat across all levels of distractor ratio, and in target trials, they resembled the mean RTs in their respective conditions. There was a speed–accuracy trade-off in the similar-orientations/target condition between seven and nine red items, as in Experiment 1. However, as previously discussed, eliminating the speed–accuracy trade-off would likely have yielded stronger linear trends in this condition.

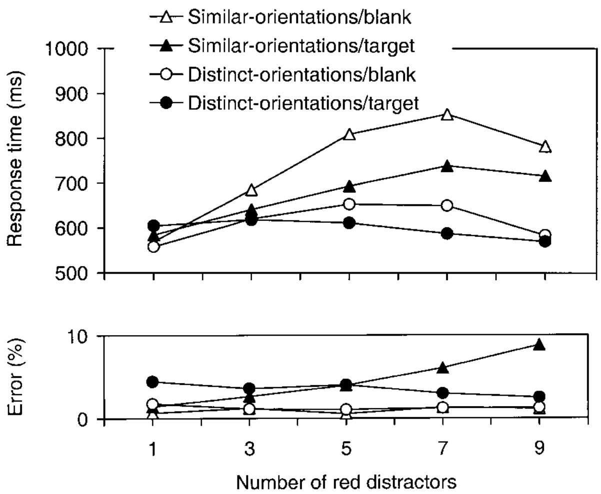

Figure 5. Mean response times (top) and error rates (bottom) in Experiment 2 as a function of distractor ratio, expressed as the number of red distractors in the display.

A three-way ANOVA of RTs revealed main effects for target presence, $F(1, 22) = 19.7$, $p < .01$; for distractor ratio, $F(4, 88) = 44.5$, $p < .01$; and for distractor orientation, $F(1, 22) = 8.90$, $p < .01$. The Target Presence × Distractor Ratio interaction, $F(4, 88) = 13.2$, $p < .01$, Target Presence × Distractor Orientation interaction, $F(1, 22) = 7.96$, $p < .01$, and Distractor Ratio × Distractor Orientation interaction, $F(4, 88) = 28.2$, $p < .01$, were all significant.

In the similar-orientations/target condition both the linear trend, $F(1, 176) = 65.3$, $p < .01$, and the quadratic trend, $F(1, 176) = 9.81$, $p < .01$, were significant, but in the distinct-orientations/target condition, just the linear trend was significant, $F(1, 176) = 4.98$, $p < .05$. The linear trend was steeper in the similar-orientations/target than the distinct-orientations/target condition, $F(1, 176) = 53.2$, $p < .01$; and the linear trend, $F(1, 176) = 65.4$, $p < .01$, and quadratic trend, $F(1, 176) = 4.61$, $p < .05$, were stronger in the similar-orientations/blank than the distinct-orientations/blank condition. As in Experiment 1, reducing the discriminability between the target's and distractors' orientations encouraged search through the group with the target's color. The results from the distinct-orientations/target condition were somewhat surprising. Not only did the quadratic trend fail to reach significance, but there was a linear trend in a direction opposite to what would have been expected if participants had been following our instructions. That is, we instructed participants to search through just the items sharing the target's color, but RTs fell with the number of red items. Perhaps, small arrays of objects do not produce sufficient bottom-up activation to reliably yield strong quadratic trends. To examine whether a larger display would have more reliably produced a quadratic trend, in Experiment 5 we measured how the quadratic trend varied when the display size increased.

The contrasts between target and blank trials were similar in Experiment 2 to what they had been in Experiment 1. Blank trials had steeper linear trends and more prominent quadratic trends than target trials; in the similar-orientations conditions: linear trend, $F(1, 88) = 15.7$, $p < .01$; and quadratic trend, $F(1, 88) = 16.9$, $p < .01$; in the distinct-orientations conditions: linear trend, $F(1, 88) = 9.65$, $p < .01$; and quadratic trend, $F(1, 88) = 9.26$, $p < .01$. As discussed previously, the results from blank trials reflect a higher average activation for distractors sharing the target's color than the target's orientation, which can be overcome if the target-orientation group is greatly outnumbered by the other group.

To test the effect of experimenters' instructions on performance, we compared each combination of condition and target presence in Experiment 2 with that in Experiment 1. Only between the similar-orientations conditions did any differences reach significance. The linear trends were stronger in Experiment 2 than Experiment 1 in both the similar-orientations/target condition, $F(1, 352) = 4.22$, $p < .05$; and in the similar-orientations/blank conditions, $F(1, 352) = 12.6$, $p < .01$. When the target's and distractors' orientations were similar to one another, participants showed a stronger tendency to search through the group with the target's color when instructed to do so.

The fact that there was an interaction of linear trends between the similar conditions, together with a lack of interaction in the distinct conditions, suggested that there might be a three-way interaction of distractor ratio, distractor orientation (similar vs. distinct), and instructions (no instructions vs. instructions). That is, we believed that the difference in linear trends between orientation conditions was greater in Experiment 2 than in Experiment 1. To support this supposition, we calculated linear contrasts of the simple three-way interaction between distractor ratio, distractor orientation, and instructional condition at each level of target presence (target trials and blank trials). The three-way simple interaction contrasts were indeed significant in both the target trials, $F(1, 352) = 4.76$, $p < .05$; and the blank trials, $F(1, 352) = 10.07$, $p < .01$. We conclude that participants in the similar-orientations condition tended to follow the experimenters' instructions more than those in the distinct-orientations condition.

As noted earlier, smaller-group search can be achieved in two different ways. The bottom-up method is to select locations with features that differ most from those in surrounding locations. The top-down method is to organize the elements into groups, determine which group is smaller, and then adopt a goal to search for the target feature belonging to the smaller group. If participants follow the instructions in Experiment 2, they will also be following a top-down, goal-driven strategy. As long as the features in both dimensions are easily discriminable, the instructions do not prompt participants to move more toward target-feature search. Participants seem to use smaller-group search as long as the feature differences permit it, which implies that smaller-group search is done with the bottom-up system based on feature differences. When one feature discrimination is difficult, participants move more toward target-feature search, which will be top-down and goal-directed. Furthermore, once the difficult orientation discrimination makes the bottom-up smaller-group search less feasible, the instructions in Experiment 2 prompt participants to move even further toward goal-driven, target-feature search. Thus, the pattern of differences between Experiments 1 and 2 fit with the idea that smaller-group search is primarily the result of bottom-up influences and that target-feature search is primarily the result of top-down influences. Experiments 5 and 6 will provide converging evidence for this conclusion.

An analysis of error rates revealed the same effects as in Experiment 1, with significant main effects of target presence, $F(1, 22) = 26.9$, $p < .01$; and distractor ratio, $F(4, 88) = 3.79$, $p < .01$;

as well as the Target Presence × Distractor Ratio interaction, $F(4, 88) = 4.15$, $p < .01$; and the Distractor Ratio × Distractor Orientation interaction, $F(4, 88) = 12.7$, $p < .01$.

Experiment 3: Brief Exposure

The patterns of RTs in the previous experiments were interpreted as reflecting covert attentional shifts. However, because the stimulus displays were visible until a button was depressed, RTs may have reflected the time taken by eye movements. The mean RTs (and therefore exposure times) were far in excess of 150 ms, the minimum latency between the onset of a peripheral stimulus and the initiation of an eye movement toward that stimulus (Carpenter, 1988). Locating the target was more difficult when one of the distractors' features was made more similar to the target's, as indicated by the significantly greater RTs in the similar-orientations conditions than the distinct-orientations conditions (see also Duncan & Humphreys, 1989; Farmer & Taylor, 1980). As the difficulty of a search task increases, it should tend more to require that individual objects be scrutinized by the high-acuity fovea, thereby increasing the likelihood of eye movements (Carrasco, Evert, Chang, & Katz, 1995; Shen et al., 2000; Williams & Reingold, 2001; Zelinsky, 1996; Zelinsky & Sheinberg, 1997). Thus, it is important to determine whether the different results between the two conditions in Experiments 1 and 2 are due to eye movements or covert attention shifts. In Experiment 3, the displays were only briefly visible, as in the experiments of Kaptein et al. (1995), to prevent eye movements.

Method

Participants. A total of 24 participants similar to those described in Experiment 1 were tested. None of the participants in Experiment 3 served in either of the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli and procedure. Whereas in Experiment 1 each trial's display was continually visible until a response was made, the displays in Experiment 3 were visible for just 150 ms. Otherwise, the stimuli and procedure were the same as in Experiment 1.

Results and Discussion

The same trimming procedure used in Experiment 1 excluded 3.8% of the total data points from analysis. RTs and mean error rates are plotted in Figure 6. An analysis of error rates revealed a main effect of distractor ratio, $F(4, 88) = 23.1$, $p < .01$. The Target Presence × Distractor Ratio interaction, $F(4, 88) = 4.62$, $p < .01$, and Distractor Ratio × Distractor Orientation interaction, $F(4, 88) = 22.6$, $p < .01$, were also significant. As could be expected from the brief exposure duration of the stimulus in Experiment 3, mean error rates were higher than in Experiment 1, most notably in the blank conditions. Apparently, the brief duration of the stimulus display prevented participants from effectively processing the image, giving rise to an increased tendency to guess (as in Chun & Wolfe, 1996). Although the error rates differed between Experiments 1 and 3, the mean error rate functions resembled the mean response curves in their respective conditions, ruling out a speed–accuracy trade-off within Experiment 3.

A three-way ANOVA of the RTs revealed main effects of distractor ratio, $F(4, 88) = 53.2$, $p < .01$; and distractor orienta-

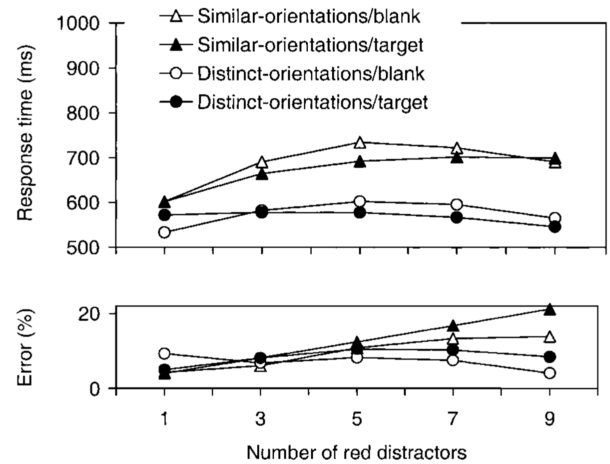

Figure 6. Mean response times (top) and error rates (bottom) in Experiment 3 as a function of distractor ratio, expressed as the number of red distractors in the display.

tion, $F(1, 22) = 21.3$, $p < .01$. There were interactions of Target Presence × Distractor ratio, $F(4, 88) = 7.56$, $p < .01$; and Distractor Ratio × Distractor Orientation, $F(4, 88) = 20.3$, $p < .01$. Finally, there was a three-way interaction, $F(4, 88) = 3.13$, $p < .05$.

As in both of the previous experiments, in the similar-orientations/target condition, there was a significant linear trend, $F(1, 176) = 89.1$, $p < .01$; and a significant quadratic trend, $F(1, 176) = 26.0$, $p < .01$. Also, in the distinct-orientations/target condition, both linear, $F(1, 176) = 6.64$, $p < .05$, and quadratic, $F(1, 176) = 4.90$, $p < .05$, trends were significant. There was a stronger linear trend, $F(1, 176) = 72.2$, $p < .01$, and a stronger quadratic trend, $F(1, 176) = 4.15$, $p < .05$, in the similar-orientations/target condition than the distinct-orientations/target condition. The linear trend, $F(1, 176) = 14.4$, $p < .01$, and the quadratic trend, $F(1, 176) = 7.34$, $p < .01$, were also stronger in the similar-orientations/blank than the distinct-orientations/blank condition. The brief duration of the stimulus failed to obliterate the effect of discriminability on the method of search.

In the similar-orientations condition, only the difference in quadratic trends, $F(1, 88) = 14.4$, $p < .01$, was stronger in the blank than target trials, whereas in the distinct-orientations condition, both the linear trend, $F(1, 88) = 17.8$, $p < .01$, and the quadratic trend, $F(1, 88) = 9.57$, $p < .01$, were stronger in blank trials. In contradistinction to Experiments 1 and 2, in which the linear trend was stronger in blank than target trials, the lack of such an effect in Experiment 3 suggests that the brief stimulus duration may have prevented a thorough search through the target-color group. Further evidence for this notion arose from contrasts between Experiments 1 and 3 that revealed the effect of brief exposure on performance. Only in blank trials did any differences reach significance. In the similar-orientations/blank condition of Experiment 3, the linear trend was more shallow, $F(1, 352) = 16.42$, $p < .01$, and quadratic trend less prominent, $F(1, 352) = 16.42$, $p < .01$, than in the similar-orientations/blank condition of Experiment 1. In the distinct-orientations/blank condition of Experiment 3, the quadratic trend was less prominent, $F(1, 352) = 5.78$, $p < .05$, than in Experiment 1. Congruent with the results of Klein and

Farrell (1989), brief exposure to the stimulus display attenuated the RT slopes in the trials that took longer to execute. This suggests that participants were able to examine all the locations with activations above threshold when there were relatively few such locations, but as the number of suprathreshold locations increased, thorough searches were replaced with guesses. Although some authors have concluded that brief exposure is an effective method for controlling eye movements (Carrasco et al., 1995) and assessing discriminability issues (Carrasco & Frieder, 1997; Eckstein et al., 2000), the present results support Klein and Farrell's assertion that it should be used with some caution.

Nevertheless, the fact that the contrasts between conditions in Experiment 3 were similar to those in Experiment 1 shows that reducing the discriminability of one of the target's features affects the deployment of covert attention independently of eye position. Even so, there may be links between the control of covert attention and the control of eye position in these conjunction searches. In a recent eye-movement study by Shen et al. (2000), the patterns in the number of fixations per trial were similar to the patterns found here in RTs.

Experiment 4: Color Differences

The previous experiments showed that if the orientation of a conjunction target is similar to the distractors' orientation, search will proceed through the group sharing the target's color. To show that this preference is not unique to color, it is necessary to show that a preference for another feature will arise when the discriminability of colors is decreased. A study by Theeuwes (1994) suggests that this may be the case. In the first of two experiments, an object with a unique color interfered with the search for a uniquely shaped object, but an object with a unique shape did not interfere with a search for a uniquely colored object. In Theeuwes's second experiment, the difference between the target's and distractors' color was decreased, and the opposite pattern was obtained. By reducing the difference between the target's and distractors' colors as in Theeuwes' study, we intended in Experiment 4 to show that search is not simply limited to a color-defined subset but that low discriminability along one dimension will promote search through the group sharing the other feature with the target.

Method

Participants. A total of 12 participants similar to those described in Experiment 1 were tested. None of the participants in Experiment 4 served in any of the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. The stimuli in the Experiment 4 included vertical and horizontal line segments, as in the distinct-orientations condition of Experiment 1, but with two colors that were much more similar than in the previous experiments. The target was a rust (CIE coordinates: .46/.43, 16 cd/m^2) vertical line segment among olive (.42/.46, 17 cd/m^2) vertical and rust horizontal distractors.

Procedure. The 12 participants tested in this experiment were all assigned to the similar-colors condition. Their performance will be compared against that of the participants in the distinct-orientations condition in Experiment 1, which will be referred to as the distinct-colors condition in the present experiment. Otherwise, the procedure was the same as in Experiment 1.

Results and Discussion

The same trimming procedure used in Experiment 1 excluded 3.9% of the total data points from analysis. RTs and mean error rates are plotted in Figure 7. As in the first two experiments, mean error rates in blank trials were low and relatively flat across all levels of distractor ratio. The inverted-U shape of mean error rates in target trials is consistent with the quadratic component present in the corresponding RTs, ruling out a speed–accuracy trade-off.

The data gathered from the 12 participants in Experiment 4 were analyzed together with the data from the distinct-orientations condition in Experiment 1. A three-way ANOVA of RTs revealed main effects of target presence, $F(1, 22) = 11.7$, $p < .01$; distractor ratio, $F(4, 88) = 27.3$, $p < .01$; and distractor color (similar colors or distinct colors), $F(1, 22) = 15.6$, $p < .01$. There were interactions of Target Presence × Distractor Ratio, $F(4, 88) = 11.3$, $p < .01$; Target Presence × Distractor Color, $F(1, 22) = 8.45$, $p < .01$; and Distractor Ratio × Distractor Colors, $F(4, 88) = 9.16$, $p < .01$. Finally, there was a three-way interaction, $F(4, 88) = 4.74$, $p < .01$.

Because the data in the present experiment's distinct-colors condition were drawn from the distinct-orientations condition in Experiment 1, the contrasts for that condition have already been reported. In the similar-colors/target condition, both the linear trend, $F(1, 176) = 16.3$, $p < .01$, and the quadratic trend, $F(1, 176) = 11.4$, $p < .01$, were significant. RTs rose more steeply in the similar-colors/target condition than in the distinct-colors/target condition, $F(1, 176) = 4.95$, $p < .05$. As can be seen in Figure 7, RTs in the similar-colors/target condition fell with increasing numbers of red items, thus rising along with the number of green items (i.e., the items with the target's orientation). Making the target's and distractors' colors more similar encouraged participants to restrict their search to the group of items sharing the target's orientation. The results from the present experiment, together with those from the previous experiments support the general claim that reducing the discriminability of one of the target's

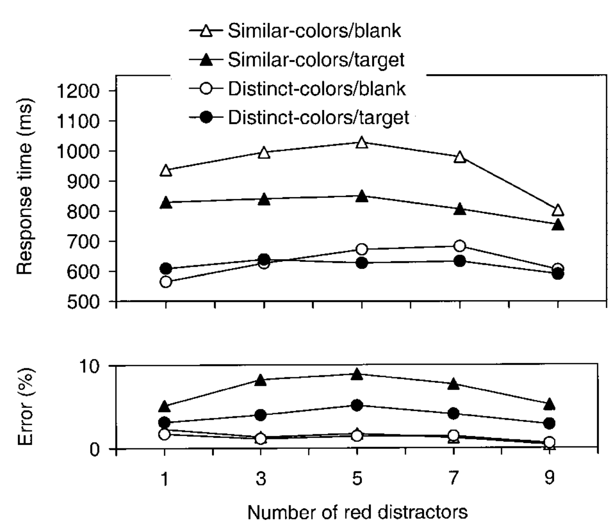

Figure 7. Mean response times (top) and error rates (bottom) in Experiment 4 as a function of distractor ratio, expressed as the number of red distractors in the display. The data from the distinct-colors conditions are from Experiment 1.

features will encourage search through the group defined by another of the target's features.

In the similar-colors condition, both the linear trend, $F(1, 88) = 3.47$, $p < .10$, and the quadratic trend, $F(1, 88) = 35.07$, $p < .01$, were stronger in blank trials than in target trials. As in the previous experiments, participants tended to search more thoroughly through the group sharing a feature with the target when none could be located, but in contrast to the previous experiments, the preferred group was the one sharing the target's orientation. It was noted above that the bias for color in the blank trials of the previous experiments could be due to more efficient grouping by color than orientation or could be due to a difference in salience between the particular colors and orientations used in these experiments. The bias toward color in the previous experiments together with the bias toward orientation in Experiment 4 support the salience account and, consequently, the applicability of the activation threshold model of search termination (Chun & Wolfe, 1996) to the present results. Thus, the bias for color in previous studies (Bacon & Egeth, 1997; Kaptein et al, 1995; Kim & Cave, 1999a; Poisson & Wilkinson, 1992) is probably attributable to the higher salience of color, rather than some intrinsic advantage of color over all other features (see also Ghirardelli & Egeth, 1998; Shen et al., 2000; Williams & Reingold, 2001). When the discriminability of the target's color is reduced, the target-orientation distractors have a higher average activation than target-color distractors. The absence of a target had a stronger linear effect in the similar-colors condition than in the distinct-colors condition, giving rise to the three-way interaction (as in Experiment 3).

In the similar-colors/blank condition, the linear trend was in an opposite direction than the linear trend in the distinct-colors/blank condition, $F(1, 176) = 4.95$, $p < .01$, indicating that the similar colors caused participants to search by orientation rather than color. There was a stronger quadratic trend, $F(1, 176) = 4.95$, $p < .01$, in the similar-colors/blank condition as well. In the analysis of error rates, only the main effect of target presence, $F(1, 22) = 16.5$, $p < .01$, the main effect of distractor ratio, $F(4, 88) = 7.77$, $p < .01$, and the Target Presence × Distractor Ratio interaction, $F(4, 88) = 6.25$, $p < .01$, were significant.

Experiment 5: Large Circular Arrays

The first four experiments generally support the claim that if both of the target's features are distinct, participants can search through the group of distractors that happens to be smaller, giving rise to a reverse-U pattern of RTs (as in Poisson & Wilkinson, 1992; Zohary & Hochstein, 1989; as well as the mixed condition of Bacon & Egeth, 1997). Although there was a significant quadratic trend in the distinct-orientations/target condition of Experiment 1 and Experiment 3, the quadratic trend failed to reach significance in Experiment 2. The unreliability of the quadratic trend may have been because the RT required to search through a group containing five elements was not much longer than for a group containing two elements. If the arrays had contained more elements, the difference in RTs between best and worst cases might have been greater than what was observed, yielding stronger quadratic trends in RTs. In other words, packing a larger number of elements onto a circle of the same radius should raise the bottom-up activations of the smaller group (Bravo & Nakayama, 1992; Todd & Kramer, 1994). The simple three-way interaction contrasts between Experiments 1 and 2 support the claim that smaller-group search is primarily a consequence of bottom-up salience, as implied by the Guided Search and FeatureGate simulations. In Experiment 5, there were displays containing 11 elements as in the previous experiments and displays with roughly twice as many elements. If the quadratic trend is stronger in the larger display than the smaller display, it will provide converging evidence that smaller-group search is primarily the consequence of bottom-up salience.

Method

Participants. A total of 12 participants similar to those described in Experiment 1 were tested. No participants served in any other experiment.

Apparatus. The apparatus in Experiment 5 was the same as in the previous experiments.

Stimuli. Experiment 5 included circular arrays with two different set sizes, containing either 11 or 21 elements. To fit all the elements onto an imaginary circle with the same radius as in the previous experiments, we made the length and width of each element (0.7° long by 0.18° wide) half of what they had been in the previous experiments. In target trials, each large array contained 2, 6, 10, 14, or 18 red horizontal distractors together with 18, 14, 10, 6, or 2 green vertical distractors. In blank trials, the target was replaced by a distractor in the same manner as in the previous experiments. Figure 2B depicts examples of displays from both conditions. Except for the smaller individual elements, the small displays were the same as in Experiments 1 and 2.

Procedure. Each participant viewed both small and large displays. The experiment began with a practice block of 20 trials followed by four test blocks. Each test block of 220 trials contained every combination of target presence (2), distractor mixture (5), target location (11), and array size (2), presented in random order. In the small-display condition, each level of target position corresponded with a single location in the display, but in the large-display condition, there were 21 positions in the display. For each block in the large-display condition, we randomly chose one of the 11 levels of target position to map onto a single position in the display; we assigned each of the other 10 levels of target position to a different pair of locations in the display. At the beginning of each trial, if the target position was 1 of the 10 that were assigned to a pair of locations, the choice between the two was made randomly. After every 110 trials, the experiment paused and participants were encouraged to take a break. Otherwise, the procedure was the same as in Experiment 1.

Results and Discussion

The same trimming procedure used in Experiment 1 excluded 4.3% of the total data points from analysis. RTs and mean error rates are plotted in Figure 8. Mean error rates in blank trials were low and relatively flat across all levels of distractor ratio, and in target trials, they generally resembled the mean RTs in their respective conditions. In the analysis of error rates, no effects reached significance; apparently, the error rates were too low for any differences to emerge. In the small-display/target condition, the error rate was unusually low when three red distractors were present. We can offer no simple explanation, except that each data point in Experiment 5 represents the mean across just 44 trials, as compared with 88 trials per data point in Experiments 1–4. Perhaps this aberration is attributable to the higher variability associated with a smaller sample size.

A three-way ANOVA of RTs revealed main effects for target presence, $F(1, 11) = 29.3$, $p < .01$; for distractor ratio, $F(4, 44) = 23.0$, $p < .01$; and for display size, $F(1, 11) = 56.8$, $p < .01$. The

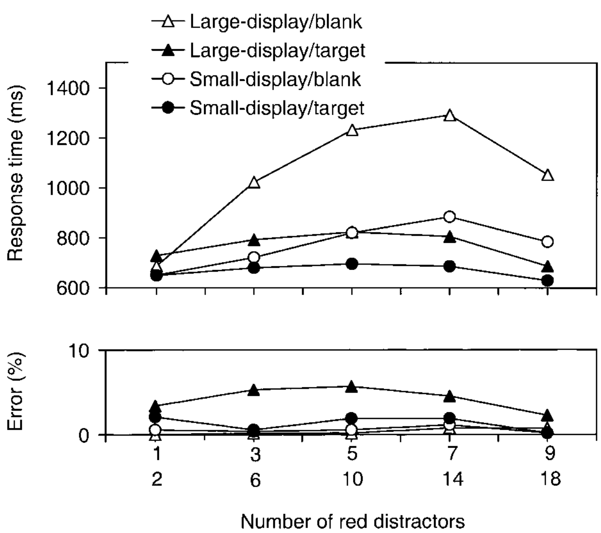

Figure 8. Mean response times (top) and error rates (bottom) from Experiment 5 as a function of distractor ratio, expressed as the number of red distractors in the display. The numbers in the top row of the *x*-axis are the numbers of red distractors in the small-display conditions, and those in the bottom row are the numbers of red distractors in the large-display conditions.

Target Presence × Distractor Ratio, $F(4, 44) = 28.8$, $p < .01$, Target Presence × Display Size, $F(1, 11) = 22.8$, $p < .01$, and Distractor Ratio × Display Size interactions, $F(4, 44) = 22.0$, $p < .01$, were all significant, as was the three-way interaction, $F(4, 44) = 15.4$, $p < .01$. In target trials, there was a quadratic trend in both the large display, $F(1, 88) = 16.91$, $p < .01$, and the small display, $F(1, 88) = 3.95$, $p < .05$, but no significant linear trends. The quadratic trend in the large-display/target condition was stronger than that in the small-display/target condition, $F(1, 88) = 5.13$, $p < .05$. In both display conditions, search was more efficient when there was a gross disparity between the distractor set sizes than when the distractor set sizes were roughly equal. This effect was amplified by the greater bottom-up signals available from the larger display, lending support to the claim that smaller-group search is primarily the result of bottom-up salience.

Experiment 6: Large, Dense Arrays

The results from the first four experiments show that reducing the discriminability of one of the target's features will encourage search through the group defined by the other of the target's features, at least when the number of objects in the visual field is small. When many more objects were present in the visual field, participants have searched through either the smaller of two groups (Zohary & Hochstein, 1989; Poisson & Wilkinson, 1992; the large-display condition of Experiment 5) or the group defined by one of a target's features when the distractor ratios were chosen to encourage it (Bacon & Egeth, 1997). Would a reduction of orientation differences induce participants to search through a color-defined subset of elements when the display size is large? Arranging the stimuli into large, dense arrays may promote smaller-group search, interfering with target-feature search for at least two reasons. First, a feature-defined group is likely to be more complex and fragmented in large displays than in displays with few elements, making top-down restriction to a feature-defined group more difficult (Theeuwes, 1996). Second, in a dense square array, each object will have as many as eight neighboring objects, whereas objects arranged on a circle have only two close neighbors. The denser concentration of elements may raise the bottom-up activations for members of the smaller group enough to exceed the top-down activations to the members of a feature-defined group (Bravo & Nakayama 1992).

Method

Participants. A total of 25 participants similar to those described in Experiment 1 were tested. The data from one participant were excluded from analysis, because this participant's mean RT exceeded the mean RT of the other participants in the same condition by a preset limit of three standard deviations. Some participants in Experiment 6 had also served in one of the previous experiments.

Apparatus. The apparatus was the same as in Experiment 1.

Stimuli. Stimulus displays consisted of 64 line segments 0.65° of visual angle long by 0.16° wide, arranged in a square grid measuring 6.2° on each side. To prevent the line segments from aligning, we displaced each segment from the center of an imaginary square cell measuring 0.78° on each side. The horizontal and vertical displacement from the center was randomly selected for each line segment to be between 0° and 0.078° (i.e., between 0 and 4 pixels up or down, left or right). At the center of the square grid of line segments was a black fixation cross measuring 0.65° on each side. A red vertical line segment (the target) was present in half the trials. The colors used in this experiment were the same as in Experiment 1. An example display from each of the two conditions is depicted in Figure 2C. Although the total number of objects (target plus both types of distractor) remained constant at 64, the relative contribution of each type of distractor varied across trials. Each trial's display was equally likely to contain 8, 16, 24, 32, 40, 48, or 56 of one type of distractor and 56, 48, 40, 32, 24, 16, or 8 of the other type of distractor. In trials with a target, a randomly chosen distractor was replaced by a target.

Procedure. As in Experiment 1, one half of the participants were randomly assigned to a distinct-orientations condition and the other half to a similar-orientations condition. A practice block of 20 trials was followed by 10 test blocks. Each test block of 56 trials contained every combination of target presence (2), distractor mixture (7), and target location (4), presented in random order. In this experiment, each level of target location corresponded to a quadrant in the square grid. Thus, a target assigned to the lower right quadrant was randomly placed at any 1 of the 16 locations in that quadrant.

Results and Discussion

The same trimming procedure used in Experiment 1 excluded 4.6% of the total data points from analysis. RTs and mean error rates are plotted in Figure 9. The analysis of error rates revealed main effects of target presence, $F(1, 22) = 48.1$, $p < .01$, and distractor ratio, $F(6, 132) = 5.24$, $p < .01$, and a Target Presence × Distractor Ratio interaction, $F(6, 132) = 3.64$, $p < .01$. The mean error rates in blank trials were low and flat across all distractor ratios, and in target trials, they resembled the corresponding patterns of RTs, indicating that there was no speed–accuracy trade-off.

A three-way ANOVA of RTs revealed main effects of target presence, $F(1, 22) = 93.7$, $p < .01$, and distractor ratio, $F(6, 132) = 46.6$, $p < .01$. In each of the first four experiments, there was a main effect of the feature manipulation; RTs were longer

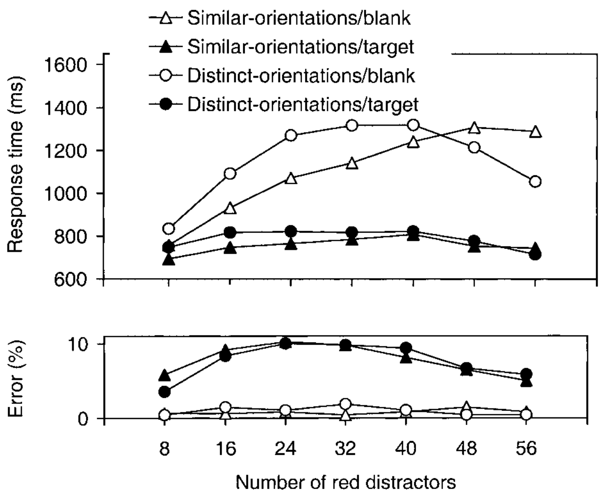

Figure 9. Mean response times (top) and error rates (bottom) from Experiment 6 as a function of distractor ratio, expressed as the number of red items in the display.

when the difference between the target's and distractors' features was reduced. In the present experiment, there was no such main effect. However, the Distractor Ratio × Distractor Orientation interaction was significant, $F(6, 132) = 10.6$, $p < .01$, as was the Target Presence × Distractor Ratio interaction, $F(6, 132) = 38.6$, $p < .01$. Finally, the three-way interaction was significant, $F(6, 132) = 7.32$, $p < .01$.

In both the similar-orientations/target, $F(1, 264) = 7.48$, $p < .01$, and distinct-orientations/target conditions, $F(1, 264) = 13.11$, $p < .01$, the quadratic trends were significant. However, in neither case were linear trends significant nor was there a difference in linear or quadratic trends between the similar-orientations/target and distinct-orientations/target conditions. These results contrast sharply with those from the previous experiments; reducing the discriminability of the target's and distractors' orientation in the present experiment encouraged participants to search through the group, sharing the target's color only when no target was present. Participants in both conditions tended to search through the smaller of two groups when a target was present; but because the experiments performed by Bacon and Egeth (1997) provided evidence for target-feature search in square arrays of 64 items, it is not the case that large-square arrays render target-feature search impossible. Why then did target-feature search arise in the experiments of Bacon and Egeth, but not in this one? In Bacon and Egeth's experiments, one type of distractor predominated across displays, and participants were instructed to search through the group of items that predominated. Perhaps in their experiments, the combined influence of skewed distractor ratios together with the experimenters' instructions induced a top-down strategy that was sufficiently robust to overcome the influence of the smaller group's salience.

Because the results from target trials were similar across conditions, the distinct results across conditions in blank trials were rather surprising. The linear trend was stronger in the similar-orientations/blank than the distinct-orientations/blank condition, $F(1, 264) = 60.6$, $p < .01$; but the quadratic trend was stronger in the distinct-orientations/blank than the similar-orientations/blank condition, $F(1, 264) = 44.3$, $p < .01$. In the similar-orientations condition, the linear trend was stronger in blank trials than target trials, $F(1, 132) = 158$, $p < .01$. In the distinct-orientations condition, both the linear trend, $F(1, 132) = 38.4$, $p < .01$, and the quadratic trend, $F(1, 264) = 72.0$, $p < .01$, were stronger in the blank than target trials. In both conditions, when participants could not locate a target quickly, they tended to search through the group, sharing the target's color more than in target trials. Whereas in target trials, participants in both conditions were equally able to exploit the increased bottom-up signals because of the denseness of the array, in blank trials, there was a clear distinction between the two conditions. In blank trials, participants in the distinct-orientations condition were better able to search through the smaller group than participants in the similar-orientations condition, who tended more to search through the items sharing the target's color.

Perhaps the most surprising aspect of the blank trial performance was that for the majority of the distractor ratios, participants with the more difficult orientation discrimination responded more quickly. There was a hint of this same effect in the target trials, which was not at all like the patterns in Experiments 1–4. Although the similar-orientations participants spent less time searching, they did not seem to pay a price in accuracy, because their error rates were comparable to those from the distinct-orientations condition. It seems that the difficult orientation discrimination prompted participants to ignore orientation differences and search through only the red items. When the orientation discrimination was easier, participants used both color and orientation information in deciding where to search, and in some cases, they were actually more thorough than the similar-orientations participants. The extra effort did not pay off in accuracy, however. It is hard to escape the conclusion that participants in the distinct-orientations condition were not optimally deciding when to terminate their search with a negative response.

Can this unexpected pattern be reconciled with activation-threshold models such as the Just-Say-No model (Chun & Wolfe, 1996)? One effect of increasing the difference between orientations is that it increases the amount of bottom-up activation. Because of these higher activations, under the right conditions an increase in the orientation difference might produce an increase in the number of distractors above the activation threshold so that terminating a search could take longer even though the discriminations are easier.

General Discussion

Previous studies have shown that effortful visual search proceeds through a subset of the entire collection of objects in the visual field. In some conjunction searches, this guidance limits search to those elements with one particular target feature, whereas in others, it limits search to the smaller group in which all elements share the same target feature. This study helps to determine when search is directed by a specific target feature and when it is directed to the smaller group. In doing so, it sheds new light on the balance between bottom-up and top-down attention systems.

Target-Feature Search Versus Smaller-Group Search

The results indicate that conjunction search is often a combination of smaller-group search and target-feature search, with the balance determined by the properties of the current stimulus and, to some extent, the instructions given to participants. Overall, fewer elements will need to be considered in smaller-group search than in target-feature search, and participants tend to engage in smaller-group search unless there is some aspect of the stimulus that makes it difficult. Participants favor target-feature search over smaller-group search only when the display size is small and the feature discrimination in one feature dimension is difficult.

Smaller-group search is still possible with a difficult feature discrimination if the display elements are numerous and packed closely together. The short distances between elements in the large display probably facilitate feature comparisons. Also, when there are just a few objects in the visual field, the expenditure of effort required to determine the members of the smaller group may not yield sufficient rewards to justify the expense.

Previous studies (e.g., Bacon & Egeth, 1997; Egeth, Virzi, & Garbart, 1984; Kaptein et al., 1995) may have fostered the conclusion that participants exert a high degree of control over the method of search, but the current results suggest otherwise. Instructing participants to choose target-feature search over smaller-group search did have some effect, but only when smaller-group search was hampered by a difficult feature discrimination (Experiment 2). This study shows that when instructions and stimulus properties are manipulated together, the stimulus properties seem to play a larger role in determining how search progresses.

Bottom Up Versus Top Down

The fact that search in these experiments is often a combination of smaller-group and target-feature searches reflects the fact that in each trial, search is guided by a combination of bottom-up and top-down factors. Models such as Guided Search and FeatureGate include a top-down system that works to select locations or objects with specified target features. The top-down system would be very important in standard conjunction searches in which the two distractor types always appear in equal numbers (Treisman & Gelade, 1980). The top-down influence can also be biased a bit in one direction by instructions, as shown in Experiment 2.

The attentional theories also include a bottom-up system to select locations or objects with unique or salient features. The bottom-up system is key to efficient feature search, but it is of little use in standard conjunction searches with equal numbers of the two distractor types. However, when one distractor type is less numerous than the other, the bottom-up system can increase the efficiency of search by limiting it to the smaller group. The strong tendency toward smaller feature search in these data suggests that the bottom-up system is hard at work here.

The bottom-up account is not the only way to explain smaller-group search; participants may first group the elements by the two target features, determine which group is smaller, and then select that group for search. Nonetheless, a bottom-up system such as that in the FeatureGate model is computationally quite simple, especially when implemented in spatial maps that analyze features from all locations in parallel. We know that grouping occurs and that it is fairly efficient, both from experiments (e.g., Kubovy, Cohen, & Hollier, 1999) and from subjective experience. However, the operations of forming the groups and determining the size of each will almost certainly be computationally more complex than the bottom-up system. Furthermore, in a neural system organized by spatial maps, grouping will require communication across long-range connections, which will be slower than short-range saliency calculations.

If smaller-group search was the product of a high-level strategy based on grouping rather than bottom-up feature comparison, then we would expect that the instructions to search by color would limit or eliminate smaller-group search. Instead, the instructions have little effect when orientations are difficult to discriminate and no effect when orientations are easy to discriminate. The data also show that smaller-group search is encouraged by easily discriminable features and by large, densely packed arrays, just as we would expect from the bottom-up account.

Recent work with split-brain patients (Kingstone, Enns, Mangun, & Gazzaniga, 1995) provides some preliminary evidence that the cortical structures responsible for limiting search to a subset of elements reside in the left hemisphere. In Kingstone et al.'s experiment, search was more efficient when one type of distractor predominated than when both distractors were equally represented but only if the target was presented to the right visual field. Because the defining features of the target were different between blocks, it seems unlikely that this advantage arose from participants limiting their search to a specific target feature. Although the authors speculated that the effect of distractor ratio was attributable to participants exerting top-down control over their search, the results from our experiments suggest that participants capitalized on the bottom-up salience of the smaller group. In any event, in order to confidently rule out a bottom-up interpretation of their results, a design in which smaller-group and target-feature search are clearly separated from one another should be used with this interesting patient group.

Covert and Overt Attention

In trials in which participants were briefly exposed to the stimulus array (Experiment 3), the pattern of results was similar to that in which displays remained visible until a response was made (Experiment 1). It seems, then, that our experiments show primarily how covert attention is deployed rather than showing how the eyes are redirected. Nonetheless, our results dovetail nicely with recent work examining saccadic selectivity in the face of manipulations of distractor ratio (Shen et al., 2000) and target feature discriminability (Williams & Reingold, 2001). That is, in conjunction searches with fixed display sizes, there were shorter latencies to make an initial eye movement and fewer fixations per trial when one or the other distractor type predominated than when both distractor types were equally represented. In blank trials, the quadratic pattern was stronger than in target trials, and the number of fixations per trial increased along with the number of distractors with the target's color. Saccades tended to land on items that were in the smaller group, with a bias for the target-color items. However, the authors (Shen et al., 2000) argued that this was a bias for the more discriminable of the target's features rather than specifically for color, because increasing the discriminability of the target's shape reduced the saccadic selectivity bias for target-color distractors.

These findings with saccades correspond closely to the results from all of our experiments, suggesting a link between control of covert attention and control of eye movements. One way to explain this link is the sequential attentional model proposed by Henderson

(1992), who claims that when the eyes are initially fixated on some location, covert attention is focused on this location as well. When the stimulus at that location has been sufficiently processed, covert attention shifts to some other location, such as the one with the next highest activation (as in the Guided Search and FeatureGate models). The location selected by covert attention is then the landing point for a subsequent eye movement. In the context of this model, eye movements are selective for the smaller group and biased toward the more discriminable of the target's features, because this is how shifts of covert attention proceed.

Implications for Models of Attention

The Guided Search and FeatureGate models of attention (Wolfe, 1994; Cave et al., 2002) suggest that smaller-group search arises primarily from the bottom-up advantage of smaller-group members. How would these models explain the increased tendency for target-feature search in the similar-feature conditions of Experiments 1 and 4? Consider the bottom-up and top-down activations of the similar-orientations condition relative to the distinct-orientations condition in Experiment 1. Within the color module, red items would generate the same amount of bottom-up activation in both conditions. However, within the orientation module, vertical items would generate less bottom-up activation in the similar-orientations than in the distinct-orientations condition, because the amount of bottom-up activation depends on the differences between the feature values. Although the amount of top-down activation generated by the presence of red would not vary across the two conditions, a line segment tilted just 20° from vertical would receive nearly as much top-down activation for orientation as a vertical item. Thus, a red distractor tilted 20° from vertical would receive nearly as much top-down activation as a red vertical target, and because the bottom-up activations of the green vertical items are attenuated relative to the distinct-orientations condition, they would be less capable of wresting control when they are the smaller group. In a competition to determine the object to which attention is directed, the target's fiercest competitors would be the red tilted distractors. As the members of this group became more numerous, search would have to proceed through more competitors, yielding the linear trend observed in the similar-orientations condition of Experiment 1. The roles of orientation and color could be reversed to model the results from the similar-colors condition in Experiment 4. Thus, the Guided Search and FeatureGate models should be able to simulate target-feature search in these circumstances without altering any parameter settings from those giving rise to smaller-group search and without explicitly grouping the objects by their features. Reproducing the effect of explicit instructions will require manipulation of the parameters controlling the top-down activation. Instructions to search for red might produce an increase in top-down activation for color, causing a stronger tendency for target-color search, as in Experiment 2.

The results from the blank trials of Experiment 3 support the inclusion of the timing mechanism that triggers guessing in the Just-Say-No model (Chun & Wolfe, 1996). The tendency to guess differs slightly in experiments with a briefly presented stimulus from experiments with a continuously visible stimulus. In the more demanding trials of a conjunction search—those in which the group through which search should proceed is relatively large—thorough search is prevented by the rapidly decaying image of the search stimulus, and thus an unsuccessful search is nearly as likely to have been a target as a blank trial. The comparable error rates between target and blank trials in Experiment 3 show that the relative probability of generating a *yes* response is quite a bit higher in experiments with a briefly visible display than experiments with continuously visible displays. The replacement of longer search trials with *yes* guesses in Experiment 3 makes it more difficult to assess the performance in blank trials. Therefore, the data from the experiments with continuously visible displays are probably more useful in testing theories of search termination such as the Just-Say-No model than those from Experiment 3.

In Experiments 1 and 4, the linear trends in blank trials show that the relative distance in feature space between target and distractor features is important in determining the amount of top-down activation assigned to different locations. If, for example, the difference between the target's color and the color of one set of distractors is smaller than the difference between the target's orientation and the orientation of the other set of distractors, then the distractors in the first group (distinct from the target in terms of color) will have a top-down advantage over the distractors in the second group (distinct from the target in terms of orientation). From the perspective of the Just-Say-No model, in blank trials the similar-feature distractors will be better represented in the group of items with suprathreshold activations. When the distinct-feature distractors are greatly outnumbered by the similar-feature distractors, their bottom-up activations should overcome the influence of the top-down advantage of the similar-feature distractors. The implications of the results from Experiment 2 are similar in blank trials as in target trials; top-down influence can be increased to benefit one of the target's features.

The results from the distinct-orientations condition in Experiment 6 may be modeled by Just-Say-No in a similar fashion as the results from the previous experiments, but the results from the similar-orientations condition represent more of a challenge. Whereas in target trials, search proceeded through the smaller group of distractors in both the similar- and distinct-orientations conditions, in blank trials, the bias for the target's color was much stronger in the similar-orientations condition. As suggested previously, perhaps the locations with the highest activations were those of a subset of the smaller group, followed by the locations with the target's color, then finally by those locations with the target's orientation. If this is the case, why would the activations of a subset of the locations with the target's orientation leapfrog above those with the target's color when the target-orientation group is smaller? One possible answer comes from the bottom-up activations, which are driven by salience. In a dense array, some members of the smaller group may be partially or completely surrounded by members of the larger group, allowing the surrounded locations to receive a large, bottom-up benefit due to the local contrast (see, e.g., Nothdurft, 1993; Poisson & Wilkinson, 1992). In the FeatureGate and Guided Search models, an object with more neighbors with different features will receive more bottom-up activation than an object with fewer different-feature neighbors. Thus, the activations of distractor locations might be ordered so that smaller-group search arises in a filled square array containing a target regardless of whether one of the features is much more discriminable than the other, but a strong bias for the more discriminable feature arises when no target is present.

Signal Detection Models

As noted earlier, current search models based on signal detection theory (Eckstein et al., 2000; Palmer, 1998; Palmer et al., 2000) provide detailed quantitative accounts of accuracy and RT data in feature searches and accuracy in conjunction searches. If our experiments were recast to measure accuracy in a two-alternative, forced-choice task with brief stimulus presentations, they might produce data that could be accounted for by a signal detection model. Furthermore, a signal detection model that is designed to translate differences in accuracy into differences in RT might be able to account for the RT data presented here.

There are, however, some qualitative results from this study that suggest that signal detection accounts by themselves will not be able to tell the whole story of visual search. First, the effect of instructions (Experiments 1 and 2) shows that search performance is not governed completely by stimulus discriminability and that any complete theory of search must include top-down mechanisms to guide search. Second, these experiments also show how the effects of featural differences between elements are enhanced when the stimuli are more numerous and packed closer together. It is possible to build interactions between nearby stimuli into signal detection models, but the current models are generally designed to account for experiments in which the stimuli are spaced far apart to minimize such interactions (e.g., Palmer et al., 2000).

Even if these issues are resolved, there are data from other attention experiments that are difficult to explain by any model that has no mechanism for selecting certain locations or objects in the visual input. In these experiments, visual search (or some other visual task) is combined with a spatial probe task to measure the degree to which some locations are selected over others. These studies demonstrate that spatial attention is at work in conjunction search (Kim & Cave, 1995), in other types of visual search (Cave & Zimmerman, 1997; Cepeda, Cave, Bichot, & Kim, 1998; Kim & Cave, 1999a, 1999b), and in other visual tasks with distractors present (Bichot, Cave, & Pashler, 1999; Kim & Cave, 2001; Kramer, Weber, & Watson, 1997). Thus, although signal detection models will probably provide insight into search performance in these tasks, spatial selection will likely remain an important part of the story.

Flexibility and Adaptability in Visual Attention

Together the results of these experiments illustrate an attention system that adapts flexibly to the tasks and stimuli presented to it. It can combine stimulus salience with knowledge of target features and use them both simultaneously to find the target as quickly as possible. When one type of distractor outnumbers the other, it can limit search primarily to the smaller group, as long as the time and effort necessary to select the elements of this group do not outweigh the search efficiency to be gained. It may not always adopt the most efficient approach, especially in deciding when to terminate a search, but it is able to take a number of factors into account and to adjust its settings to produce efficient search.

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