Journal of Experimental Psychology:
Human Perception and Performance
1990, Vol. 16, No. 4, 879-892

0096-1523/90/$00.75

Limitations on the Parallel Guidance of Visual Search: Color × Color and Orientation × Orientation Conjuctions

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In visual search for a conjunction it is much more difficult to search for the conjunction of 2 colors or 2 orientations than for Color × Orientation or Color × Shape conjunctions. The result is not limited to particular colors or shapes. Two colors cannot occupy the same spatial location in Color × Color searches. However, Experiments 6 and 7 show that Color × Shape searches remain efficient even if the color and shape are spatially separated. Our guided search model suggests that in searches for Color × Shape, a parallel color module can guide attention toward the correct color, whereas the shape module guides attention toward the correct shape. Together these 2 sources of guidance lead attention to the target. However, if a target is red and green among red–blue and green–blue distractors, it is not possible to guide search independently toward red items and green items or away from all blue items.

This article deals with the limitations on the ability of the parallel stage of visual processing to guide the subsequent serial deployment of attention. Following Neisser (1967), many models of visual processing feature a preattentive stage, where some amount of initial processing is done in parallel across all locations in the visual field, and a later attentional stage, where a spotlight of attention restricts processing to a region of the field. Performing an attentional task at multiple locations requires serial processing, with the focus of attention moving from one location to another (e.g., Hoffman, 1978, 1979; Julesz & Bergen, 1983; Treisman & Gelade, 1980). In her studies of visual search, Treisman concluded that the parallel preattentive stage of processing could only identify simple attributes in a few features (e.g., color, motion, and orientation). Searches for more complex items or for conjunctions of simple features required attention and thus serial search (e.g., feature integration theory; see Treisman, 1986, 1988; Treisman & Gelade, 1980; Treisman & Gormican, 1988).

This research was supported by National Eye Institute of the National Institutes of Health Grant EY05087, the Whitaker Health Sciences Fund, the Educational Foundation of America, and the Massachusetts Institute of Technology class of 1922.

We thank Alice Yee, Charles Pokorny, Bob Sugiura, Felicitas Treue, John Martello for help with the experiments, and IBM for the loan of YODA graphics boards. Many people provided useful comments on earlier versions of this article. We particularly thank Anne Treisman, Kathy O'Connell, David Irwin, Michael D'Zmura and Daphne Bavelier.

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More recently, evidence has accumulated that although the parallel modules may be limited to the analysis of simple features, searches for conjunctions of those features need not require a random, serial, self-terminating search (Egeth, Virzi, & Garbart, 1984; Nakayama & Silverman, 1986; Steinman, 1987; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989). A modification of feature integration theory can explain these data if parallel feature-finding modules are allowed to guide attention. We call it the *guided search model* (Wolfe & Cave, 1990; Wolfe et al., 1989; for a precursor, see Hoffman, 1978, 1979). For example, suppose that the target is a red vertical line and that the distractors are green vertical and red horizontal lines, a conjunction of color and orientation. A parallel module sensitive to color could not find the target item, but it could guide attention toward red items and away from green items. An orientation module could guide attention toward vertical items and away from horizontal items. By combining these two sources of information, a "spotlight of attention" (Posner & Cohen, 1984) could be guided to the red vertical target.

In the guided search model, there are bottom-up and top-down components to the guidance provided by the parallel feature modules. Each is computed separately for each type of feature. At each location in the field, *bottom-up* activity increases exponentially, with the mean of the differences between the stimulus at that location and the stimuli at all other locations.[1] In the example of conjunction search given

[1] It would probably be more accurate to base bottom-up activation on a comparison with all items within some neighborhood. Neighborhood effects will be incorporated in a forthcoming revision of the basic model.

before, half of the items are red and half are green. Since each item is different from half of the other items, all items have the same bottom-up activation for color (similarly for orientation). In the case of a simple feature search for a target among homogeneous distractors, the unique item would receive very strong bottom-up activation and would easily attract attention. Indeed, Pashler (1988) and Jonides and Yantis (1988) showed that it is very difficult *not* to direct attention to a unique item (see also Miller, 1989).

Top-down activation is based on the similarity between the stimulus and the known properties of the target. Obviously, unlike bottom-up activation, top-down activation requires knowledge of the identity of the target. Thus, if the target is known to be a red vertical line, red items receive strong top-down activation in the color module, and vertical items receive strong activation in the orientation module.

In the guided search model, the two sources of activation for each module together with a noise term are summed to produce an overall activation map. The activation map preserves no information about the origins of the activation; it only guides attention to the most active location. If that does not prove to be the target, attention proceeds to the next-most active location, and so on. The search terminates when the target is found. If no target is found, the search terminates when the activation of the most active remaining location falls below some minimum threshold. (One can propose other constraints on the movement of attention; for example, see Koch & Ullman, 1984.)

The free parameters of the model are the magnitude of the noise terms, the threshold for termination of search, and the relative strength of each feature dimension. In a feature search for a unique item among homogeneous distractors, the bottom-up activation of the target is very large. It is almost always greater than the activation produced by noise, and thus attention is immediately directed to the target regardless of the number of distractors. In the aforementioned conjunction example, the target and distractors items receive equal amounts of bottom-up activation. Half of the items receive top-down activation for color; another half receive top-down activation for orientation. In the summed activation map, the target is distinguished from the distractors by having two sources of top-down activation. This advantage is much smaller than in the feature search case, and noise is more likely to cause attention to be misdirected toward distractor items. As the noise parameter is varied, slopes for conjunction searches can vary from essentially parallel to completely serial at the point where any guidance is lost in the noise. The same variations in the noise parameter have no influence on feature searches (Wolfe & Cave, 1990).

The same type of variation in slopes for conjunction searches can be produced by holding the noise constant and varying the effectiveness of the guidance by manipulating stimulus salience (e.g., contrast, color saturation, etc.) or other properties of the display (homogeneous vs. heterogeneous distractors). The differences between our highly efficient conjunction searches and previous serial results may be explained in these terms (Wolfe, Cave, & Franzel, 1989).

In this article we examine an important limitation on the guidance of attention. Specifically, though it is possible to guide attention to an item defined by a conjunction of different types of features (e.g., Color × Orientation), it is not possible to guide attention to an item defined by two instances of the same feature type (e.g., Color × Color or Orientation × Orientation). A series of control experiments shows that this failure of guidance is not due to the specific choice of colors or the spatial configuration of the stimuli. Rather, it appears to be due to a basic difference between a search for something that is red and vertical, for example, compared with a search for something that is red and green or vertical and oblique. Although we present these results in the context of our guided search model, we are not presenting them as a prediction of that model. Rather, the inability to search efficiently for within-feature conjunctions is a property of the visual system that any model must explain. In the General Discussion section, we consider the ways that this finding constrains visual search models.

Experiment 1: Color × Color and Orientation × Orientation Conjunctions

The first experiment tests the ability of the parallel processes to guide attention toward candidate targets defined by a conjunction of two instances of a single feature type (two colors or two orientations).

Method

Apparatus. Stimuli were presented on a standard TV monitor that was part of a modified *Sub-Roc 3-D* video game. Displays were controlled by an IBM PC–XT with IBM-YODA graphics. Stimuli were presented in an 11.3° × 11.3° field with a small central fixation point. Individual items could be presented at any of 36 locations in a slightly irregular 6 × 6 array. On each trial items were presented at 8, 16, or 32 randomly chosen loci within the array. On target trials one of these loci contained a target item. Set size, positions of target and distractors, and presence or absence of a target were random across trials. Subjects responded by pressing one of two keys: *yes* if a target was detected and *no* if it was not. Reaction times (RTs) were measured from the onset of the display. All stimuli were presented at the same time by adjusting a color table. Because of video refresh, items at the top of the display could appear up to 17 ms before items at the bottom. The stimulus remained visible until the subject responded, and feedback was given on each trial. Targets were present on 50% of trials. All experiments in this article were variations of this visual search paradigm.

Two versions of Experiment 1 were conducted: one with Color × Color conjunctions and the other with Orientation × Orientation conjunctions. In the color version stimuli were colored squares 0.85° on a side. These were divided in half vertically by a black line. Target items were half red and half green; distractors were red and blue or green and blue. (CIE [Commission Internationale de l'Eclairage] x, y coordinates: red = .62, .36; green = .34, .57; blue = .14, .07). In the orientation version stimuli were composed of 0.85°-long vertical, horizontal, or oblique (45°) lines. Lines could be black or white on a gray background. Each item was composed of one black and one white line. Using line elements of different luminance polarities reduced the salience of the overall item shape and forced subjects to base their search on the orientation of the lines. The luminance polarity of the lines was irrelevant to the task. Targets were composed of vertical and oblique lines; distractor items were vertical and horizontal or oblique and horizontal. An example of the orientation task is shown in Figure 1.

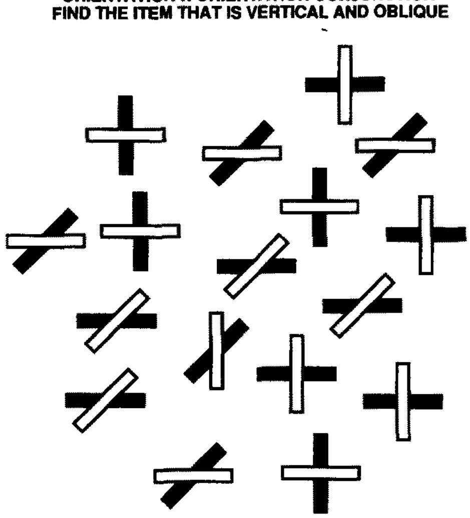


Figure 1. An example of an Orientation × Orientation conjunction. (Target is vertical and oblique. Distractors are vertical and horizontal or horizontal and oblique. Lines of different luminance polarity are used to weaken the overall shape cue that could be used to discriminate target and distractors.)

Subjects. Subjects were drawn from the Massachusetts Institute of Technology undergraduate subject pool. All gave their informed consent in advance, were paid for their participation, and were unaware of the purposes and methods of these experiments. All had at least 20/20 acuity, using correction as needed. Subjects were tested for 330 trials each: 11 were tested in the color version, and 10 were tested in the orientation version. Methods for all other experiments in this article were similar to those of Experiment 1.

Results

For each subject average RTs were determined for each set size for target-present and target-absent trials. Trials with RTs of greater than 5,000 ms or less than 200 ms were discarded and not replaced. Slopes and y intercepts of the RT × Set Size functions were computed by a linear regression. Figure 2 shows average RT as a function of set size and trial type for the Color × Color version. Data for a Color × Orientation search are shown for comparison (T: red vertical; D: red horizontal, green vertical). Results for the Color × Color condition are consistent with serial self-terminating search. The main effects of set size are significant for target trials, $F(2, 20) = 102.3$, $p < .001$, and for blank trials, $F(2, 20) = 97.4$, $p < .001$. The difference between target trials and blank trials is significant, $F(1, 10) = 49.2$, $p < .001$, as is the interaction of set size and trial type, $F(2, 20) = 27.0$, $p < .001$. Error rates are 3.2% at set size 8, 5.6% at size 16, and 11.4% at size 32. The effect of set size on error rate is significant, $F(2, 20) = 15.8$, $p < .001$. The slopes of blank trials, and target trials appear to be in the 2:1 ratio predicted by serial search. The average slope ratio is 2.0, and all 11 fall between 1.1 and 2.9.

Figure 3 shows average data for the Orientation × Orientation conjunctions. The results are comparable to those for Color × Color conjunctions. The main effects of set size are significant for target trials, $F(2, 18) = 116.2$, $p < .001$, and for blank trials, $F(2, 18) = 202.9$, $p < .001$. The difference between target trials and blank trials is significant, $F(1, 9) = 312.0$, $p < .001$, as is the interaction of set size and trial type, $F(2, 18) = 22.3$, $p < .001$. Error rates are 4.4% at set size 8, 9.4% at size 16, and 11.7% at size 32. The effect of set size on error rate is significant, $F(2, 18) = 8.8$, $p < .001$. The slopes of blank trials and target trials appear to be in the 2:1

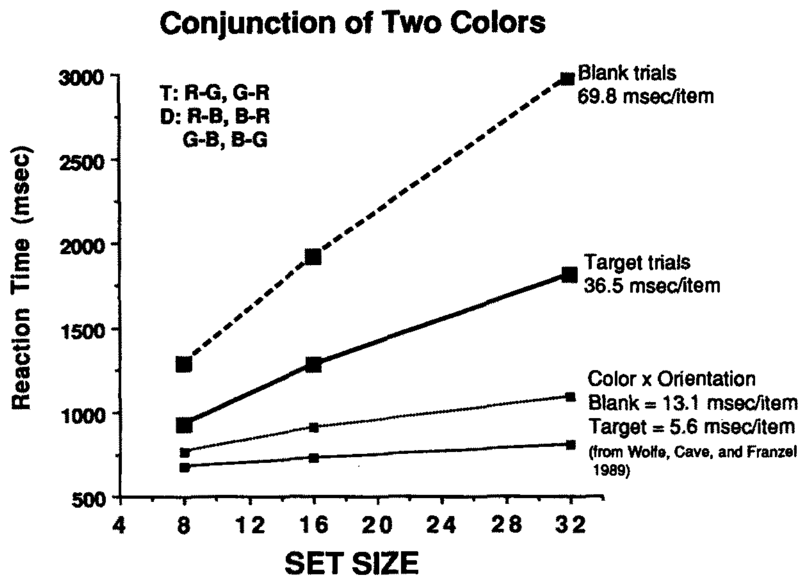


Figure 2. Subjects searched for an item defined by the presence of two colors (red and green) among items containing one of those colors (red and blue or green and blue). (Average RTs for 10 Ss; search functions are steep. The much shallower functions for a conjunction of color and orientation are shown replotted from Wolfe, Cave, & Franzel, 1989.)

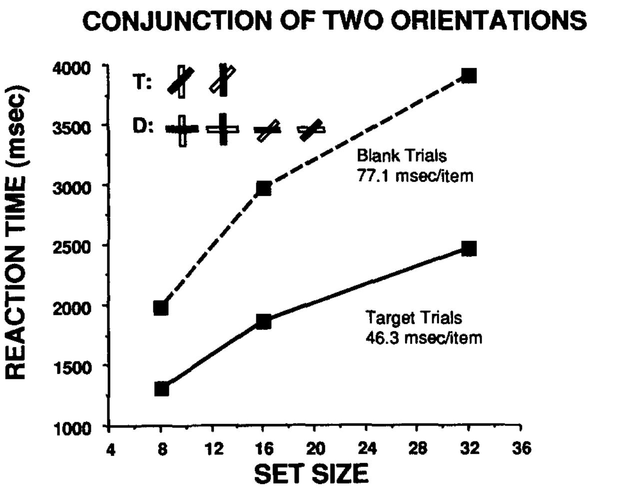


Figure 3. Subjects searched for an item defined by a conjunction of two orientations (see Figure 1). (Average RTs for 10 Ss; search functions are steep.)

ratio predicted by serial search. The average slope ratio is 1.7, and all 10 fall between 1.0 and 2.6. The 1.7 average is not significantly lower than the predicted 2.0, $t(9) = 1.97$, $p > .05$.

Discussion

Searches for conjunctions of two instances of a single feature type are much more difficult than conjunctions across features. A comparison can be made with data from Wolfe et al. (1989). Experiment 2 of Wolfe et al. presents results from a Color × Orientation search that used stimuli similar to those used here. These data are replotted in Figure 2. The Color × Orientation search is much more efficient than the Color × Color or Orientation × Orientation searches, with average slopes of about 6 ms/item for target trials and 3 ms/item for negative trials. Error rates are much lower (<5%) in the Color × Orientation case.

We argue that there is a basic difference between searches for conjunctions between two feature types and searches for conjunctions between two instances of the same feature type. Before basing any such conclusions on this result, however, several alternative explanations must be considered.

1. Searches for Color × Color or Orientation × Orientation conjunctions could be perceptually difficult; that is, it might take a relatively long time to determine if an individual item was red and green. Thus a protracted search through a limited number of items could appear to be an exhaustive search through the entire set.

2. Color searches are easy when a target color is presented among distractors of homogeneous color. Perhaps this search is difficult because of the nonhomogeneous distractor colors.

3. The target in Experiment 1 was red–green. Perhaps the choice of roughly opponent colors contributed to the difficulty of the search.

4. Perhaps the search is made difficult by the spatial configuration of the items (two adjacent rectangles).

5. Unlike red and vertical, red and green colors or vertical and oblique orientations cannot exist in exactly the same place at a single moment. Perhaps it is difficult to search for items that lack this spatial overlap or integrality.[2]

We examine and reject each of these hypotheses before returning to a general discussion of searches for Color × Color and Orientation × Orientation conjunctions.

Experiment 2: Perceptual Difficulty

If attention must be deployed in a search task, the speed of the movement of attention is governed by two factors. First, it takes some fixed amount of time for attention to disengage from its current location and move to a new location. Second, once at a new location, the spotlight must linger long enough to allow for the performance of the relevant perceptual task. This second factor is usually assumed to be roughly constant and of short duration relative to the first factor. If this is not true for some tasks, then the slopes of RT × Set Size functions might be inflated by factors not directly related to the mechanics of the visual search. For a somewhat extreme example, if a subject were required to find a cluster of 24 dots among distractor clusters containing 23 dots, we might imagine that the bulk of the time would be spent counting the dots in each cluster and not moving attention from cluster to cluster.

In the context of the present experiments, it could be proposed that red–green or vertical–oblique stimuli are difficult to identify. Thus, even if guided search is possible and limited to a subset of the items in a Color × Color or Orientation × Orientation search, the slopes of the RT × Set Size functions might still be steep if attention were required to linger for many milliseconds at each attended location. To test this hypothesis, Color × Color, Orientation × Orientation, and Color × Orientation conjunctions were presented with a set size of 1. There is no search in this case, only identification.

Method

Stimuli were identical to those used in Experiment 1, except that the line elements in the Orientation × Orientation stimuli were yellow and blue, not black and white. Color × Orientation stimuli were identical to those used in the Color × Orientation experiment plotted in Figure 2 (T: red vertical; D: green vertical, red horizontal). The single stimulus could be positioned anywhere in the 11.3° × 11.3° field. Ten subjects ran 30 practice trials and 100 experimental trials in each of the three conditions.

Results and Discussion

Individual and average results are given in Table 1, and results of paired t tests are given in Table 2. There are no significant differences between Color × Color and Color × Orientation stimuli. It did take substantially longer to identify Orientation × Orientation stimuli. It is clear that differences

[2] To be more accurate, two colors cannot coexist in the same place and retain their separate identity. Red and yellow could coexist as orange, and there is some evidence that mixtures of this sort are treated differently from unique or cardinal hues (see D'Zmura & Lennie, 1988; Treisman & Gormican, 1988).

Table 1
Results for Experiment 2: Reaction Times for Simple Identification of Stimuli in Three Conjunctions

	Target trials			Blank trials		
Subject	Orientation × Color	Color × Color	Orientation × Orientation	Orientation × Color	Color × Color	Orientation × Orientation
MIS	377	358	398	381	365	439
JER	397	386	423	457	423	464
SVJ	424	515	746	541	611	848
JMW	456	378	370	464	381	395
CWP	389	383	437	408	426	438
SLP	358	403	535	385	438	517
SRF	357	342	518	386	462	537
EJH	434	447	504	466	470	572
JM	419	401	448	461	460	503
AT	456	457	569	604	482	579
Average	407	407	495	455	451	529

in the time required to identify an individual item cannot be used to explain the differences in search time for Color × Color versus Color × Orientation tasks. Returning to Figures 2 and 3, it is clear that the overall RT for Orientation × Orientation tasks is slower than that for Color × Color tasks, just as the identification RTs in Experiment 2 are slower for Orientation × Orientation tasks than for Color × Color tasks. Given the similarity in the slopes for these two tasks, it seems possible that with our stimuli the Orientation × Orientation task required a constant additional time for each trial, regardless of set size. This may reflect a subject's need to double-check an answer.

Experiment 3: Color Searches With Heterogeneous Distractors

A search for a red–green item among red–blue and blue–green items could be difficult because of the presence of three colors in the display (e.g., see D'Zmura & Lennie, 1988). A search for a standard conjunction (e.g., red vertical among green vertical and red horizontal) involves only two colors (or orientations). In the context of the guided search model, searches get more difficult as the number of colors increases, because each item is different from a greater proportion of the other items. To test the magnitude of this effect, subjects performed a simple feature search for color with highly heterogeneous distractors.

Table 2
Paired t-Test Results for Experiment 2

	Conjunction					
	Orientation × Color		Color × Color		Orientation × Orientation	
Conjunction	*t*	*p* <	*t*	*p* <	*t*	*p* <
Orientation × Color	—		0.02	.98	2.5	.05
Color × Color	0.02	.87	—		3.8	.005
Orientation × Orientation	2.2	.056	3.8	.005	—	

Note. *df* = 9. Paired *t* tests for target trials are above the diagonal; *t* tests for blank trials are below the diagonal.

Method

Ten colors were generated. The CIE coordinates and luminance values are given in Table 3. Colors were not equated for luminance; however, the targets were neither the brightest nor the dimmest in the set. Two versions were run. In one case the target was red (Color 1 in Table 3). In the second version the target was purple (Color 6 in Table 3). Distractors were the remaining nine colors. Ten subjects were tested for 30 practice trials and 300 experimental trials evenly divided among target trials and blank trials at set sizes 8, 16, and 32. No distractor color appeared more than once per trial for size size 8, no more than twice for size 16, and no more than four times for size 32. In all other respects the experiment was similar to Experiment 1.

Results

Figure 4 shows average RTs for both versions. For the red target condition the effects of set size were not significant, $F(2, 18) = 0.82$. For the purple target condition, the effects of set size, though small, were reliable: slopes 4.1 ms/item on target trials, 8.8 ms/item on blank trials; $F(2, 18) = 10.1$, $p < .005$. The difference between the red and purple versions was significant, $F(1, 9) = 15.8$, $p < .005$. Error rates averaged 1.8% and did not interact significantly with either target color or set size.

Table 3
Colors for Experiment 3

	CIE coordinate		
Color	x	y	Luminance (cd/m^2)
1. Red	0.607	0.366	0.350
2. Yellow	0.463	0.462	1.710
3. Green	0.341	0.589	0.960
4. Blue-green	0.252	0.332	0.680
5. Blue	0.180	0.078	0.130
6. Purple	0.376	0.218	0.280
7. Orange	0.528	0.428	0.980
8. Gold	0.457	0.427	0.920
9. Lavender	0.369	0.291	0.860
10. Sky blue	0.300	0.335	0.940

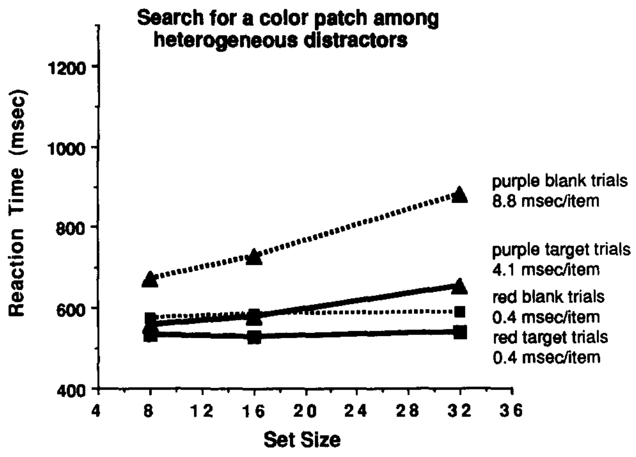


Figure 4. Subjects searched for an item of one color (red in one case, purple in the other) among distractors of nine heterogeneous colors. (Efficient parallel search is possible even when the target color is not the "odd man out.")

Discussion

Several conclusions may be drawn from the results of this control experiment. First, given that a very efficient search is possible with a distractor set of nine different colors, it is unlikely that the presence of three colors is the primary cause of difficulty in the Color × Color experiment. Second, the ability to search for a target of one color even when each distractor item is of unique color is further evidence for the top-down component of search proposed in the guided search model. Finally, the significant difference between red and purple versions could be considered a form of search asymmetry (Treisman & Souther, 1985). In our stimulus set the red is more extreme and has fewer neighbors in color space. Top-down activation of purple may activate some items of similar color. These would be rejected when checked by attention, producing a slight slope on the RT × Set Size function. D'Zmura and Lennie (1988) provided a more sophisticated analysis of this problem. For us the important conclusion is that heterogeneity of colors is inadequate as an explanation of the difficulty of Color × Color conjunction searches.

Experiment 4: Nonopponent Color Pairs

In Experiment 1 the target was red–green: These are roughly opponent colors. Certainly, they are not strictly opponent, as each is simply the product of the red or green gun of the cathode-ray tube in isolation. Nevertheless, it might be thought that even quasiopponent colors might produce some problems for search. Accordingly, we have repeated the basic experiment with a nonopponent target color pair.

Method

In honor of the bicentennial of the French revolution, subjects searched for the French tricolor (red–white–blue or blue–white–red) among red–white–green, green–white–red, blue–white–green, and green–white–blue distractors. Obviously, the white region in the middle is irrelevant, and this is simply a search for red–blue items among red–green and green–blue items. Stimuli were larger than those in Experiment 1 (1° × 2° with a 2° black "flagpole" on a gray background). Set sizes were 1, 4, 8, and 12. Ten subjects were tested. All other aspects of the methods were similar to the previous experiments.

Results and Discussion

Figure 5 gives average results. The slopes, 43 ms/item for target trials and 64 ms/item for blank trials, are comparable to those obtained with red–green targets in Experiment 1. In another version of the basic Color × Color experiment, subjects searched for red–yellow targets among red–blue and blue–yellow distractors. Average slopes were 28.8 ms/item for target trials and 47.5 ms/item for blank trials. Apparently, choice of colors is not critical, and the results of Experiment 1 cannot be explained by the near opponency of the target colors.[3]

Spatial Characteristics of the Stimuli

Two or more different feature types can occupy the same spatial location (i.e., a single item may be big, red, vertical, etc.); two instances of the same feature type cannot. The same location cannot be both red and green without a mixing of the two colors. The processes involved in a search may consider a stimulus like the red and green target used in Experiment 1 to be two separate items. It is possible that the searches in Experiment 1 are serial because it is more difficult to search for conjunctions across items than within items. Experiments 5–7 deal with this issue.

There are two approaches to this problem that do not successfully address the issue. First, one could attempt to put two colors in almost the same place by making a pattern consisting of very small intermixed spots of Color 1 and Color 2. Even if the regions of different color are still visible (e.g., a red–green grating), the relatively coarse grain of the visual subsystem for color tends to blend the colors introducing a color-mixing artifact (color assimilation; see Hurvich, 1981). Using the colors in Experiment 1, color mixing yields a trivial search for a yellow target among purple and blue–green distractors. D'Zmura and coworkers (see D'Zmura & Lennie, 1988) did a series of interesting experiments on searches for color targets that either are or are not mixtures of the distractor colors. These illuminate other aspects of the parallel process-

[3] The choice of stimuli in this experiment was prompted by the hypothesis of a French graduate student that great familiarity with the target might increase search efficiency. Her results (target trials, 32.8 ms/item; blank trials, 44.7 ms/item) suggest that familiarity may help. Her RTs are significantly shorter than those of the rest of the subjects at all set sizes except set size 1 ($p < .05$, one-tailed t test) and the slope of her RT × Set Size functions are shallower than the average slope ($p < .05$, one-tailed t test). Nevertheless, her search remained resolutely serial. Of course, many factors beyond the patriotic may be relevant here, and no serious conclusions can be drawn with data from a single subject. These data do suggest that experiments on the effects of practice may be of interest.

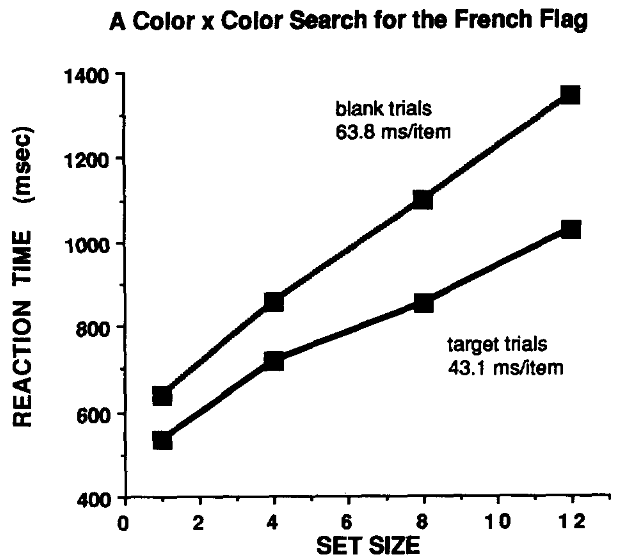


Figure 5. A replication of Experiment 1 with different stimuli. (Here the target was a French tricolor [red–white–blue]. Distractors were red–white–green and green–white–blue. Colors could appear in the reverse sequence [e.g., blue–white–red]. Search is serial, replicating the basic finding and showing that the target need not be a conjunction of opponent or near-opponent colors.)

ing of color; however, it seems clear that for visual search purposes an item with red and yellow subfields is not the same as an orange item. They may both be conjunctions of red and yellow, but they remain qualitatively different.

The second method involves temporal alternation of two colors in the same place. If the rate of alternation is relatively high (>15–20 Hz), the colors fuse, producing color mixture again. When the alternation rate is slower, pilot work indicates that the task is very difficult, with foveal scrutiny required to determine the colors alternating at any given location.

Two more viable approaches are possible. First, different spatial configurations can be tried in an effort to make a red-green target that is clearly a single item, or at the very least to prove that the results of Experiment 1 are not dependent on the particular stimuli used (Experiment 5, as follows). Second, although two examples of one feature type cannot be placed in a single location, it is possible to separate two different features spatially (e.g., color and shape). If conjunction across space is inherently difficult, guided search should be impaired when the two features do not occupy the same spatial location (see Experiments 6 and 7).

Experiment 5: The Shape of the Stimuli

Method

Figure 6 shows an array of stimuli that were used in replications of Experiment 1. Several versions were run with the rectangular stimuli of Experiment 1. Some had a black line running through the middle of the stimulus, and some did not. *Center-surround* stimuli were used to have the center of gravity of each of the colored regions fall in the same location even if the colors themselves could not overlap. *Dumbbell* stimuli were thought to look more like a single item than side-by-side rectangles. Dumbbell stimuli were enclosed inside a square to group the two colors more convincingly and to isolate them from other items. Like dumbbells, × and *plus* stimuli were thought to look more like single items. A variety of set sizes were used in different experiments. In most cases, targets were the two possible versions of red–green items, and distractors were the two versions each of red–blue and green–blue items. One dumbbell experiment used only one of the two red–green targets and one each of the red–blue and blue–green distractors. The × and plus experiments substituted white for blue in the distractors. Conditions are summarized in Figure 6. Ten subjects were tested in each version of the experiment. Many subjects were tested in more than one version. Practice of this sort does not appear to alter the results.

Results and Discussion

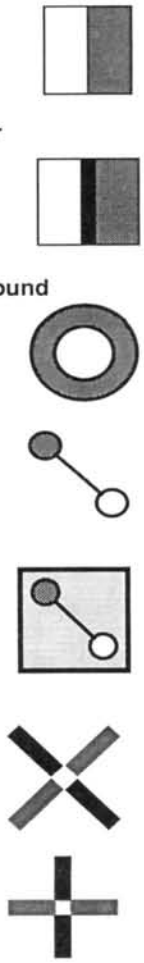
The average slopes for target (Y = yes) trials and blank (N = no) trials are given in Figure 6 for each of the stimuli. The final column gives the ratio of the blank slopes and target slopes. Though there is some variation from condition to condition, it is clear that all of the stimuli produced data consistent with serial search. Across conditions the average slope was 35.6 ms/item for target trials and 66.0 ms/item for blank trials. These slopes are on the steep side of the normal estimates for serial searches (Treisman, 1988). The average slope ratio was 1.9, not significantly different from the 2.0 predicted by serial self-terminating search.

The differences between conditions are interesting. There is quite a range in average slopes. The plain rectangle and center-surround stimuli produce slopes of roughly 20 ms/item on the target trials and 40 ms/item on the blank trials. Other conditions, notably the dumbbell stimuli and divided rectangles, show roughly twice that slope: 40 ms/item on target trials and 80 ms/item on blank trials. This 2:1 relationship suggests that subjects may have been able to ignore 50% of the distractor items in the easier searches, though they still required serial search through the remaining items (cf. Egeth et al., 1984). Local color contrast is a cue that may have made some of the tasks easier than others. The easier searches all had colored regions directly adjacent to one another. The blue-green border is less perceptually salient than the red–green or red–blue. In other experiments, we have found that local color contrast can be used as a cue in visual search, a topic we will address in a future paper. The × and plus targets with close but not adjacent color regions appear to produce intermediate results. The important point is that serial search was required for all of the stimuli used in Experiment 5 and that when color contrast is minimized as a cue, those searches yield estimates of the search time necessary per item that are slower than the usual 40–60 ms/item.

Experiment 6: Standard Conjunctions With Spatial Separation Between Features

As noted previously, conjunctions between two instances of one feature type necessarily involve conjunctions between two spatial locations. Although Experiment 5 demonstrates that several spatial configurations produce serial search for Color × Color conjunctions, it could be that spatial separation

COLOR X COLOR CONJUNCTIONS WITH VARIOUS STIMULI



Stimulus	Targets	Distractors	Set Sizes	Avg Slopes Y	N	N/Y
Rectangular	t:rg, gr	D:rb,br,gb,bg	8 16 32	17.9	36.6	2.0
	t:rg, gr	D:rb,br,gb,bg	1 3 6 8 16 32	20.7	40.5	2.0
Rectangular with a line	t:rg, gr	D:rb,br,gb,bg	8 16 32	37.0	70.0	1.9
Center-surround	t:rg, gr	D:rb,br,gb,bg	2 4 8	20.0	36.0	1.8
Dumbbell	t:rg, gr	D:rb,br,gb,bg	8 16 32	43.0	77.0	1.8
	t:rg	D:rb,bg	8 16 32	48.0	92.0	1.9
Dumbbell in a box	t:rg, gr	D:rb,br,gb,bg	2 4 8	58.7	77.2	1.3
	t:rg, gr	D:rb,br,gb,bg	2 4 8	47.4	86.3	1.8
"X"	t:rg, gr	D:rw,wr,gw,wg	8 16 32	27.3	60.3	2.2
Plus	t:rg, gr	D:rw,wr,gw,wg	8 16 24 32	38.8	74.0	1.9

Figure 6. Stimuli and results for 10 further replications of the Color × Color experiment. (Note that in all cases slopes of RT × Set Size functions are steep and generally show an approximate 2:1 ratio between blank trial and target trial slopes.)

between attributes is the common cause of these serial searches. Perhaps serial search is required for any task requiring conjunction between two locations. Experiment 6 tests this hypothesis.

Method

Although it is not possible to put discrete red and green regions in the same place, it is possible to go in the opposite direction and create a red vertical target in which red is in one location and vertical is in another. Examples of such stimuli are shown in Figure 7 for a conjunction of color and shape. There are two versions of a Color × Shape conjunction in Experiment 6. In both cases, the target is the item that has the attributes red and C. In the first case, red and C are in the same location. In the second case, they are in different locations, with an achromatic C and the color placed in a separate horizontal bar. In the *same* condition the horizontal bar is included to keep the spatial configuration constant across conditions; however, it is achromatic and irrelevant to the task. Distractors in both conditions were green and C and red and I (as shown in Figure 7). For comparison purposes a Color × Color conjunction was run with similar stimuli (bottom of Figure 7). Ten subjects were each tested in all three conditions. Order of testing was randomized across subjects. Set sizes 4, 8, 16, and 32 were tested. Each subject was tested for 30 practice trials and 300 data trials per condition.

Results and Discussion

The average RT data are shown in Figure 8. Looking first at the *same* condition, the average slopes of 5.5 ms/item for target trials and 9.9 ms/item for blank trials are comparable to those obtained in our lab with simpler Color × Shape conjunction stimuli (Wolfe et al., 1989). Although the *different* condition does produce somewhat steeper slopes than the

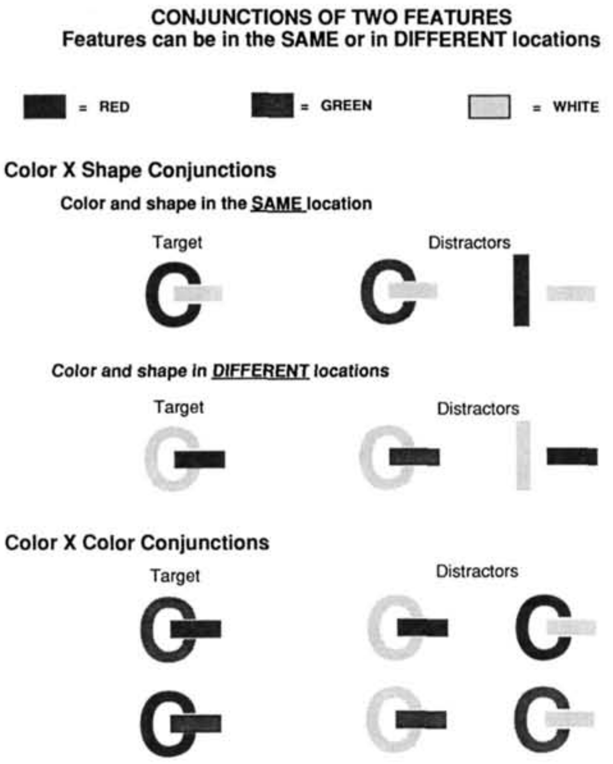


Figure 7. Stimuli for Experiment 6. (Color and shape can be expressed on the *same* stimulus element or on two *different* elements. The target is a red C. In the *same* case, the horizontal bar is achromatic and irrelevant. In the *different* case, the critical shape is achromatic and the color is carried on the horizontal bar. This mimics the Color × Color conjunction case, where red and green are expressed on different elements. The final condition is a Color × Color conjunction that uses similar stimuli.)

same condition, the difference is not significant: target trials, $t(9) = 0.6$, $p > .5$; blank, $t(9) = 1.5$, $p > .15$. Moreover, the difference is entirely due to the anomalous data of one subject whose slopes in the *different* case are more than six standard deviations greater than the average slopes of the remaining 9 subjects. Removing this subject's data, the average slopes in the different cases are 4.6 ms/item for target trials and 6.0 ms/item for blank trials. Clearly, guided search is still possible for Color × Shape conjunctions when the relevant color and shape attributes are spatially separate.

By contrast, the Color × Color condition replicates the previous Color × Color results. The average slopes are similar to those produced by Color × Color conjunction searches in the previous experiments. They are significantly steeper than the slopes for *same* or *different* versions of the Color × Shape conjunctions, $t(9) > 3.9$, $p < .005$, for all comparisons. Removing the anomalous subject from the analysis does not change these results. The comparison among the Color × Color condition and the two Color × Shape conditions is complicated by a difference in the distractor set. In the Color × Shape conditions, half of the distractor items contain an *I*. All distractors in the Color × Color condition were of the same shape. The additional variation in the distractor set might be expected to make the Color × Shape task more difficult (Duncan & Humphreys, 1989), which it is not, of course. In a less likely account, it could be argued that the I stimuli were simply not considered to be items and that the effective set size in the Color × Shape conjunctions could be half of the nominal set size. To determine if this factor could explain the difference between the Color × Color and Color × Shape results in this experiment, the Color × Shape slopes were doubled and then compared with the slopes for the Color × Color condition. With the anomalous subject removed from the analysis, the hypothesis that Color × Color slopes are twice as large as Color × Shape slopes is rejected, $t(8) > 2.6$, $p < .05$, for all comparisons. That is, the Color × Color slopes are significantly steeper than twice the Color × Shape conjunctions.

The overall conclusion from Experiment 6 must be that spatial separation alone does not disrupt guided search. However, it may still be objected that Color × Color and Color × Shape tasks are not sufficiently similar to allow for fair com-

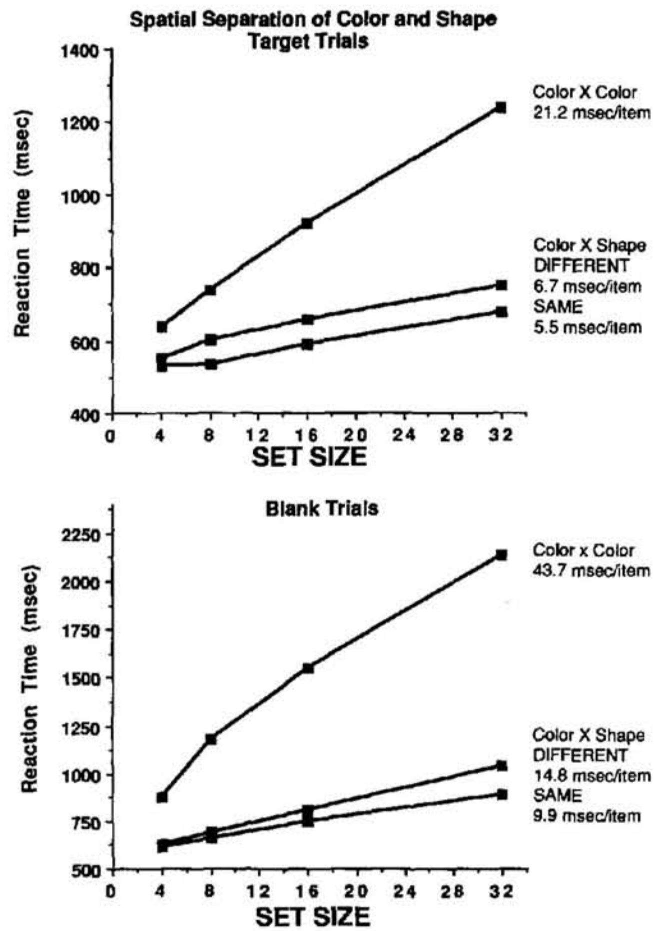


Figure 8. Results for Experiment 6 showing that placing color and shape on different stimulus elements makes little difference to the search task. (In both cases, search is more efficient than predicted by a serial self-terminating search. Spatial separation between target features is not the explanation of the steep slopes for Color × Color conjunctions.)

parisons. Perhaps if a Color × Orientation condition that was truly comparable to a Color × Color condition were tested, both would be completely serial. It is surprisingly difficult to design these truly comparable conditions. For example, in Experiment 6, the Color × Shape condition contains shapes, say, that are not present in the Color × Color condition. One could introduce the I stimuli into the Color × Color distractor set, but then I stimuli would need to be introduced into the Color × Color target set as well. This would put the Color × Color condition at a disadvantage, and so on. We have designed many experiments that address the issue of spatial separation. As a service for those who seek to disprove the main thesis of this article, we now discuss two ways to do this type of experiment incorrectly.

The flawed stimuli are shown in Figure 9. In the top task, the target was a plus sign composed of a red vertical and a green horizontal bar. The distractors were combinations of red horizontal, green vertical, and yellow and blue vertical and horizontal bars. There were no red vertical or green horizontal elements in the distractors; thus in principle one could do the task with a search for either of those elements. On the basis of our previous results, this should yield guided search. When we conducted the experiment, however, the average slopes were 20.1 ms/item for target trials and 42.2 ms/item for blank trials, a result consistent with serial search but not guided search. In retrospect, it is clear that this is not

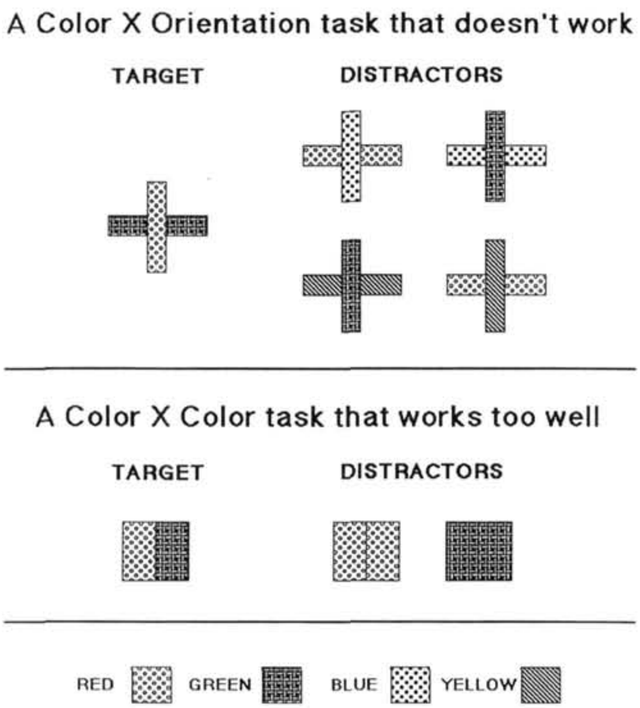


Figure 9. Stimuli for two cautionary experiments. (In the first, a Color × Orientation task is made difficult by the presence of both the target color and orientation in distractor items, albeit in different parts of those items. In the second, a Color × Color task is made easy by the presence of two cues: size [target is small red or small green] and local color contrast [the red–green border serves as a texton gradient].)

a search for red vertical or green horizontal elements. Suppose that a subject searched for items that were red and vertical. Though no distractor contains a red vertical element, two of them do contain red and vertical elements, albeit on separate elements of the item. Experiment 6 demonstrated that parallel processes can guide the search for conjunctions when the two attributes are spatially separated. These results suggest that it is hard for those processes *not* to guide search, even when it is disadvantageous. The rules that govern the spatial deployment of parallel guidance are not clear at the present time. We do not know what defines an *item* for visual search purposes. For us, however, this condition makes a cautionary point. Guided search seems to make little distinction between two features that are present in a single stimulus element and two features that are in the same item but spatially separated.

In the second task the target was a box, half red and half green. The distractors were boxes that were either all red or all green. This was designed as a simple Color × Color conjunction. On the basis of preceding experiments in this article, this should yield a slow serial search. In this case the average slopes of the RT × Set Size functions were 4.4 ms/item for target trials and 6.8 ms/item for blank trials. Clearly, this search is much more efficient than any of the other Color × Color searches described in this article. The results are comparable to those obtained with many feature searches. Again, the results can be explained by inadvertent properties of the stimuli. There are at least two factors at work here. First, the task could be done on the basis of size or a conjunction of size and color. The target is not only red and green. It also contains the only small red or small green elements. The second factor is local color contrast. The target contains a high-contrast color border; the distractors do not. As discussed in connection with Experiment 5, other experiments show that local gradients attract attention (texton gradients; see Julesz, 1986). This seems to have been at work in this case, and it cautions the experimenter to be on guard for unintentional cues that can make otherwise-serial tasks into parallel tasks. With these concerns in mind, Experiment 7 repeats this Color × Color condition correctly and compares the results with an Orientation × Color task.

Experiment 7: Color × Color Versus Color × Orientation Conjunctions

Method

Stimuli. The stimuli for Experiment 7 are shown in Figure 10. Each stimulus is a white bar with two embedded colored regions. In the Color × Color task, the target has one magenta and one green region, and the distractors have either two magenta or two green regions. All bars are vertical. In the Color × Orientation version, the target is a vertical bar with two magenta regions. The distractors are magenta horizontal and green vertical. The green and magenta were of the same luminance (dimmer than the white bar). The white bar tended to mask the size effects discussed in Experiment 6. The two colored regions were separated by a distance sufficient to attenuate the color contrast effects discussed before. In a second version of the experiment, the colored regions are placed on black bars on a gray background. This manipulation was intended to increase the apparent saturation of the colored patches.

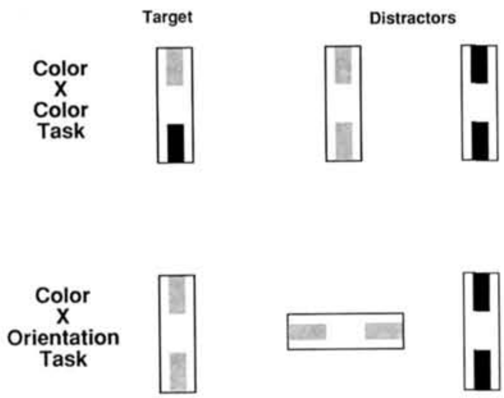


Figure 10. Stimuli for a comparison between Color × Color and Color × Orientation searches. (Note that the distractors differ only in the presence of a second orientation in the Color × Orientation case. This should make the Color × Orientation case more difficult.)

Ideally, identical distractor sets would be used in the Color × Color and Color × Orientation conditions. As discussed previously, this is not as easy as it might seem. If the Color × Color condition used the distractors from the Color × Orientation condition, then half of the distractors could be discounted on the basis of their orientation. A second target could be introduced: It would be horizontal, magenta, and green. Now, there would be two types of Color × Color targets and only one Color × Orientation. Moreover, the experiment falls prey to the problem that beset the first task in Experiment 6. An item that is horizontal, green, and magenta is also horizontal and green for visual-search purposes. Similarly, the vertical, magenta, and green item is vertical and magenta. Since the distractor items do not contain horizontal and green, this nominal Color × Color task can be done as a pair of guided searches for either magenta vertical or green horizontal items.[4]

Given the actual stimuli for Experiment 7, the only difference between the distractors in the Color × Color and Color × Orientation tasks is the presence of an additional orientation in the Color × Orientation case. If anything, the greater heterogeneity in the distractors should make the Color × Orientation task more difficult (Duncan & Humphreys, 1989). Set sizes were 1, 4, 8, and 12. Eleven subjects were tested in each condition. In other respects, this experiment resembled previous experiments in this article.

Results and Discussion

Average results are shown in Figure 11.[5] Clearly, the Color × Color task is much less efficient than the Color × Orientation task. Beginning with the white bars, paired t tests show the slopes to be significantly steeper in the Color × Color task: target trials, $t(10) = 4.9$, $p < .001$; blank trials, $t(10) = 5.2$, $p < .001$. The average slope ratio for the Color × Color task is 1.9, with a 95% confidence interval from 1.6 to 2.3. This is consistent with a serial self-terminating search. By contrast, the average for the Color × Orientation search is 2.6, with a 95% confidence interval from 0.1 to 5.2, reflecting the wide range of individual slope ratios found in guided search (Cave & Wolfe, 1990). With the black bars the results are similar. In this case too, the Color × Color task was significantly less efficient than the Color × Orientation task: target trial slopes = 15.2 ms/item for Color × Orientation, 26.8 ms/item for Color × Color; blank trial slopes = 20.6 ms/item for Color × Orientation, 42.5 ms/item for Color × Color, for both paired t tests, $p < .05$. The experimental design of Experiment 7 argues again that there is no basic procedural difference between within-feature (Color × Color) and between-feature (Color × Orientation) conjunctions that penalizes within-feature conjunctions. The targets are of the same form in the two tasks. The distractors are of the same form as well, except that there is an extra orientation in the Color × Orientation task. These results support the contention that efficient guidance is not possible for within-feature conjunctions.

General Discussion

Searches for conjunctions between two instances of a single feature type are significantly less efficient than searches for conjunctions between two features. The stimuli are not difficult to identify in isolation (Experiment 2). The parallel guidance by color does not appear to be limited to stimulus sets involving only two colors (Experiment 3). The result is not an artifact of the particular colors or shapes used in the original experiment (Experiments 4 and 5). Finally, the search for conjunctions of two spatially separated features is not necessarily more difficult than the search for standard conjunctions (Experiments 6 and 7). We conclude that there is a basic difference in our ability to locate conjunctions between two features and conjunctions between two instances of the same feature type.

The results of these experiments can be modeled within the context of the guided search model. However, they should not be seen as evidence for that model over all alternatives. Rather, these results constrain any models of the structure of the parallel stage of processing. For example, it is now necessary to distinguish between two classes of model that have previously been used interchangeably. Consider the structure of Figure 12, derived from Treisman (1985, Figure 9; 1988, Figure 1). Separate maps exist for different colors, sizes, orientations, and so forth. Each of these maps has an input to the attentional level of processing. In terms of the guided search model, each map would be capable of guiding attention. The results of the Color × Color and Orientation × Orientation searches argue against this structure, because in this version the search for an item that is red and green is not logically different from the search for an item that is red and vertical.

Figure 13 shows a slightly different structure, similar to a slightly different version of Treisman's model (Treisman, 1986). Separate processing for different colors, orientations, and so forth remains. Psychophysical and physiological findings make it clear that such selective processes (or *channels*) exist. However, for purposes of guiding attention, there is now a distinction between conjunctions within feature mod-

[4] In fact, we ran this condition and the results are consistent with the hypothesis that subjects did perform a pair of guided searches.

[5] Because a set size of 1 is an identification task and not a search task, slopes are based on set sizes of 4, 8, and 12. Indeed, an inflection in the slope can be seen at set size 4 for the target trials.

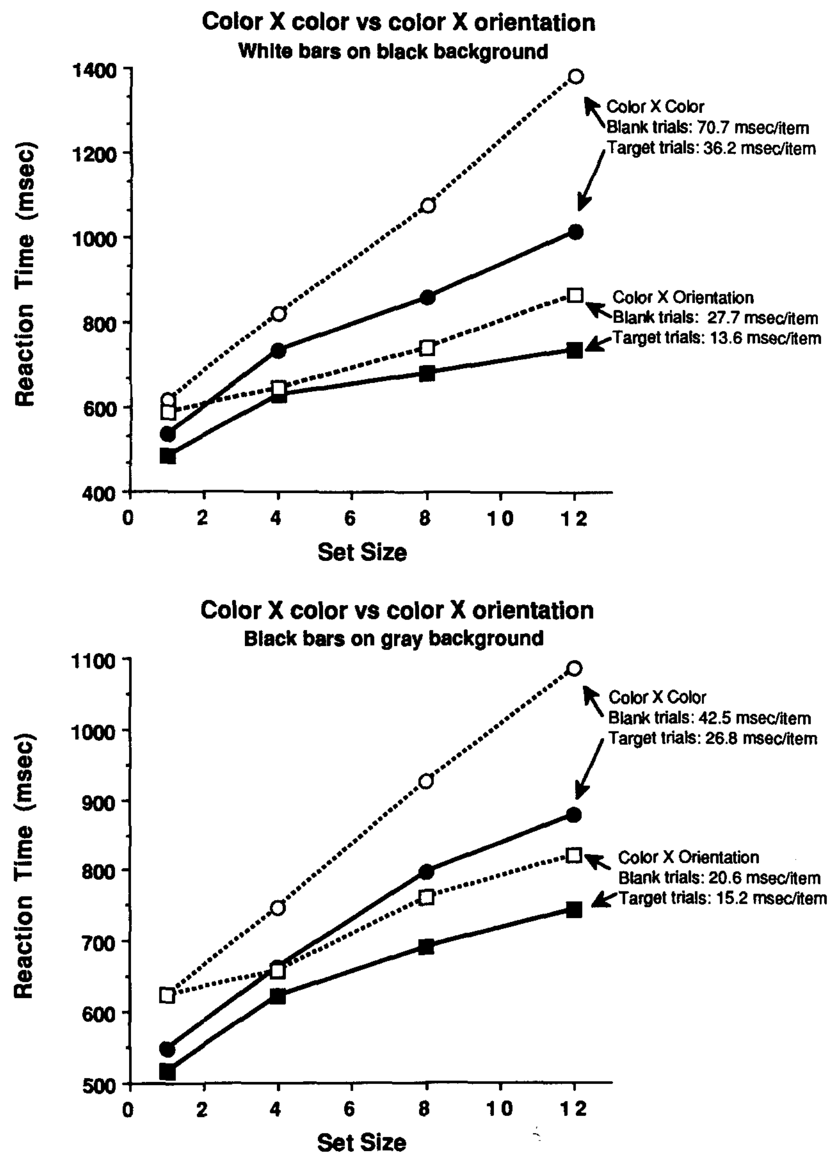


Figure 11. Results for Experiment 7 showing that Color × Color searches are significantly less efficient than comparable Color × Orientation searches.

ules and between feature modules. We believe that the distinction can be understood in terms of simple logical operations on the sets of items. In a standard conjunction search for a red vertical item, the color module can find the set of all red items, the orientation module can find the set of all vertical items, and attention can be guided to the intersection of those two sets. By contrast, in a search for a red and green item, the color module can find the set of all red items and the set of all green items, but for purposes of guiding attention the result appears to be the union of the two sets. When all items contain either red or green, this sort of guidance is useless.

This account assumes that the color module can and does find the set of all red items and the set of all green items at the same time. An alternative would be that the color module or any one feature module is incapable of dealing with more than one attribute at one time. Our data incline us toward the former account (Wolfe, Yu, & Stewart, 1989).

The serial nature of searches for conjunctions of two instances of the same feature type argues not only against a structure in which each instance (red, green, vertical, etc.) has modular status (Figure 12); it also argues against models in which no modularity exists in the parallel stage. For example, Duncan and Humphreys's (1989) similarity theory conceives of the parallel stage of processing as a single multidimensional space. In this space, the greater the distance from targets to distractors, the easier it is to find the target while the greater the distance between different distractor types, the harder it

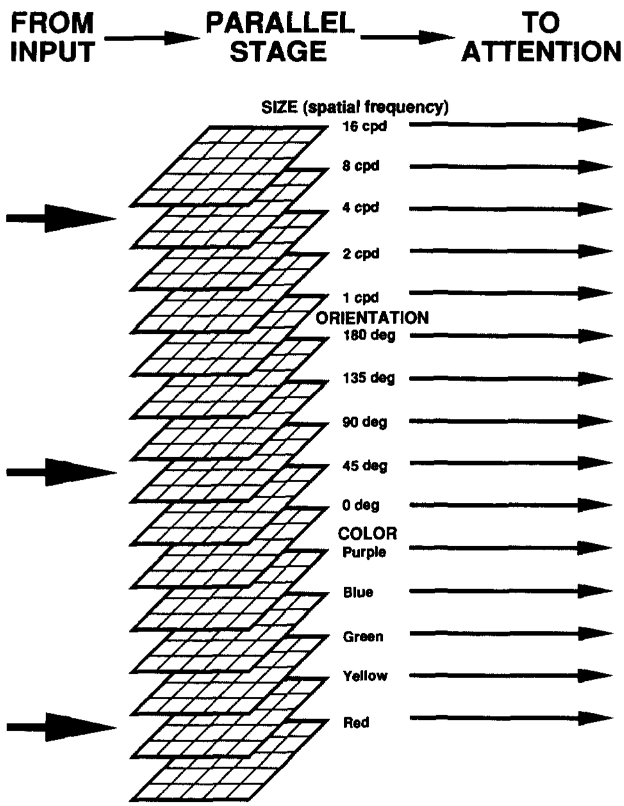


Figure 12. A possible organization for the parallel stage of processing (based on Treisman, 1985). (Each instance of a feature type sends input to the serial stage of processing. The data argue against this structure.)

is to find a target. This is similar to a guided search, except that it makes no distinction between conjunctions within feature types and between feature types. To explain the serial results from Color × Color and Orientation × Orientation searches, this theory would need to assert that distance in similarity space from one color to another color or one orientation to another orientation is generally less than the distance from a color to an orientation. For example, the distance from a red–green item to a red–blue item would be less than the distance to a red vertical item. With similarity scaled in such a way, this model would probably account for the Color × Color and Orientation × Orientation data. However, by making large distances between features like orientation and color, this would reintroduce a version of modularity by feature. Such a model would be very similar to ours.

The results of these experiments reveal another limitation on the ability of the parallel modules to guide attention. In principle, in the guided search model the parallel modules could guide attention (a) toward targets by activating candidate target locations or (b) away from distractors by inhibiting distractor locations. There are at least two versions of guidance by inhibition. First, the parallel modules could inhibit all locations containing a distractor attribute. Thus, in a standard Color × Orientation conjunction, a color module could inhbit all green locations. Second, the parallel modules could inhibit locations that do not contain a target attribute. Thus in the previous example the color module could inhibit all locations that are not red. This distinction between what might be called *direct* and *double-negative* inhibition is important, because the present results rule out the direct case but say nothing about the double-negative case. Taking the Color × Color search of Experiment 1 as an example, all of the distractors contained the color blue. If it were possible to guide attention away from all blue locations, the only remaining location would have been the target. There is no evidence of such guidance. By contrast, although there might be a physiological difference between activation of candidate targets and double-negative inhibition of items that are not candidate targets, there is no difference at the level of description provided by the current guided search model.

It is much harder to search for a conjunction of two instances of the same feature type than to search for a conjunction between instances of two different feature types. Our data show that this is not an artifact of the properties of a single spatial configuration or of the choice of colors. The data are consistent with a structure for the parallel stage in which each feature type provides only a single source of guidance to the subsequent deployment of attention in visual search.

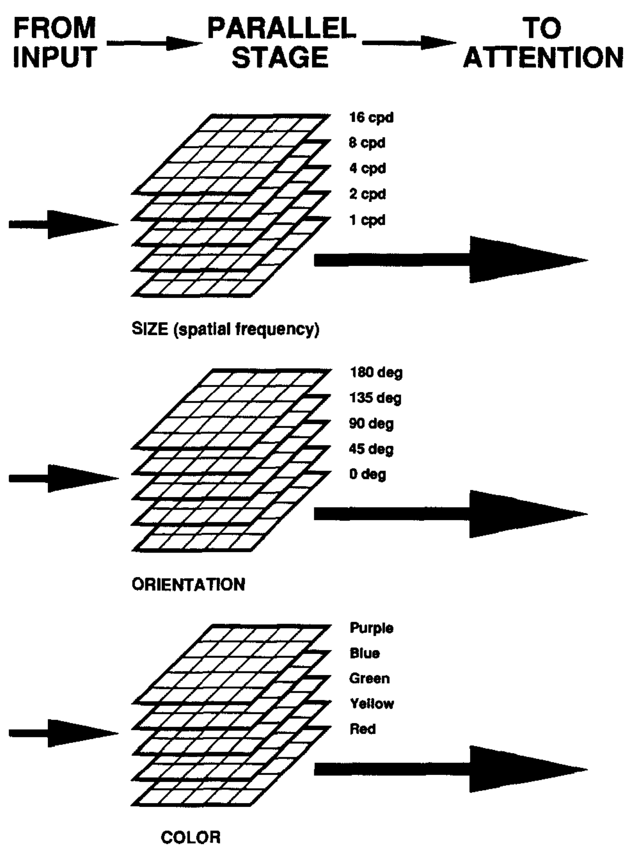


Figure 13. Another possible organization for the parallel stage of processing (based on Treisman, 1986). (Only a single input to the serial stage of processing is allowed from each feature type [color, size, etc]. The data argue in favor of this structure.)

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Received January 26, 1989
Revision received March 28, 1990
Accepted March 13, 1990 ■