

Luminance and Edge Information in Grouping: A Study Using Visual Search

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Preattentive grouping is supported by 2 systems, a brightness system that is contrast polarity sensitive and an edge system that is relatively insensitive to contrast polarity. Search was spatially parallel for pairs of same contrast polarity vertically aligned circles, among horizontal pairs, and serial for pairs of circles that had the opposite contrast polarity (Experiments 1–3). By replacing the circles with squares, the authors investigated the effect of adding collinear edge information. When collinear edges were present, the polarity difference between paired items did not disrupt grouping (Experiments 4–6). These results support models of grouping in which brightness and edge information are processed separately (e.g., S. Grossberg & E. Mingolla, 1985) and models of visual search in which complex relations between stimuli can be computed in parallel across the display.

A basic question for understanding the encoding of visual displays concerns the nature of the visual information that can be encoded in a spatially parallel manner. Over the past 20 years, considerable research effort has been given to this question, often using the visual search procedure (e.g., see Triesman, 1988). In the visual search task, participants are asked to decide as quickly as possible whether a predesignated target is present in a display. Parallel search is indicated by a relatively minor effect of the display size on the search efficiency; search rates at or below 10 ms/item are sometimes taken as a benchmark (e.g., Heathcote & Mewhort, 1993) because such search rates are difficult to realize within a biologically plausible serial processing system (Crick, 1984).

Much of the early work on visual search supported the view that only simple properties of displays are encoded in parallel, such as the color, size, or orientation of elements. In contrast, search for targets defined by relationships between these simple features, such as a particular form–color

conjunction, leads to inefficient search: Reaction times (RTs) for display size search functions are typically of the order of 30 ms/item. Also, in the latter case, RTs are linearly related to the display size, and the slope of the function for absent responses is about double that for present responses (e.g., Triesman & Gelade, 1980). Such a pattern of results is consistent with conjunction search requiring a serial self-terminating exploration of the display (e.g., Triesman, 1988; though see Humphreys & Müller, 1993, and Townsend, 1972, for alternative accounts of such search functions).

Recently, however, evidence has indicated that more complex image descriptions can be encoded in parallel. For example, target block figures that share two-dimensional orientations with distractors, but that differ in their encoded three-dimensional orientations, can be detected efficiently in search tasks, with slopes often of 10 ms/item or less being observed (Enns, 1990; Enns & Rensink, 1991). Similarly, efficient detection has been observed for surfaces formed by continuous patterns of shading where targets differ from distractors in the orientation of their derived three-dimensional surface (Ramachandran, 1988). Search for targets defined by size differences relative to distractors was influenced by the relative scaling of their size on the basis of local projective depth information (Humphreys, Keulers, & Donnelly, 1994). Such results suggest that the relationship between image features, at least within the form domain, can be encoded in parallel to produce efficient search.

Other complex stimuli relationships can also be extracted in parallel. For example, studies have shown efficient (parallel) detection for line elements that group on the basis of two-dimensional closure (Donnelly, Humphreys, & Riddoch, 1991; Elder & Zucker, 1993). The present research continues in this tradition and assesses whether another two-dimensional grouping factor, collinearity, is encoded in parallel across visual displays. We also had a second aim in the present experiments, which was to assess the nature of

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the information that might be used to compute collinearity. Elder and Zucker (1993) investigated the effect of contrast polarity on closure by varying the contrast polarity of the line segments that made up the closed group. When adjacent line segments within each shape had the same contrast polarity and were closed, targets could be detected efficiently; however, this was not the case when adjacent line segments in the shapes had opposite contrast polarity (e.g., one lighter and one darker than the background). Such a result suggests that closure based on line segments may be computed in parallel with the use of primitive representations that are sensitive to contrast polarity, hence closure breaks down when lines of opposite polarity are used. In the present study, we used visual search techniques, with the elements to be grouped being solid regions, to examine whether parallel coding of collinearity was affected by the contrast polarity of edges.

Prior studies of how form elements group into collinear edges are ambiguous on the point of whether grouping is influenced by polarity of contrast. Demonstrations such as the reverse polarity Kaniza figure (Figure 1) suggest that grouping based on collinearity may be relatively insensitive to reversing the polarity of contrast between elements. This has lead theorists such as Grossberg and Mingolla (1985) to propose that grouping by collinearity may operate on edge representations that are insensitive to polarity of contrast. However, it is possible to group elements to produce oriented stimuli with primitives that are not orientation coded. For instance, a series of dots may be grouped to form "oriented blobs" by sampling the image at a low spatial frequency.

If such blurring operates on primitives that are sensitive to the polarity of contrast, then grouping would be disrupted by having adjacent elements with opposite contrast polarities (blurring a dark and a light element together would produce an area close to the brightness of the gray background). Similarly, grouping would be disrupted if it were based on a comparison of token representations of the stimuli in the image, linking elements that had either the same, absolute, or relative brightness (e.g., see Marr, 1982).

In the present study, we examined two factors: (a) the

relative efficiency of coding targets and distractors based on the grouping between elements that either do or do not have intrinsic orientations (circles vs. squares) and (b) how grouping between these different primitives was influenced by the relative polarity of contrast of the adjacent elements.

In all the experiments (except Experiment 5) participants performed search tasks in which targets and distractors always consisted of the same two local elements: In the distractors the elements were horizontally aligned and in the target the elements were vertically aligned. Detection of the target relative to the distractors required that the elements that made up the target be grouped together. The two main factors that were varied were the shape of the elements and the contrast polarity within target or distractor pairs. The efficiency of grouping and whether it operated in parallel across the visual field can be assessed by measuring search efficiency as a function of the display size.

Experiment 1 assessed the effect of polarity of contrast on the grouping of circles to form oriented stimuli by contrasting search for targets and distractors composed of circle elements either with the same or with the opposite polarities of contrast. Experiment 2 was a control study conducted with circles differing in brightness, but with the same polarity of contrast, to ensure that effects of contrast polarity were not simply due to luminance differences between adjacent elements. Experiment 3 was another control study that assessed whether effects due to the use of within-group elements with opposite contrast polarities were indeed due to the disruption of within-form grouping rather than to the introduction of competing between-form grouping, between elements with the same contrast polarities in target and distractor groups. Experiment 4 compared performance when squares (with oriented collinear edges) were used rather than circles (without oriented, collinear edges) and assessed whether qualitatively different grouping mechanisms come into operation when edges are present. Experiment 5 was a control experiment that assessed whether target pairs of squares were being detected using the strong horizontal internal contour. Experiment 6 investigated one possible mechanism by which the presence of the edge information could lead to the grouping being polarity insensitive.

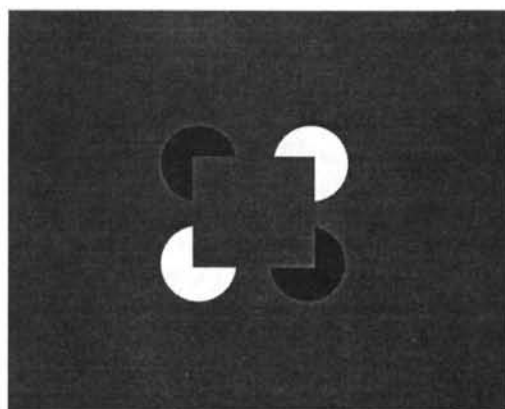


Figure 1. The reverse polarity Kaniza figure.

General Method

The general method was used for all the experiments, although in Experiment 4 there was a slight change in the design.

Participants

All experiments were performed on adult volunteers whose ages ranged from 19 to 37 years. The volunteers were associated with the University of Birmingham and were either paid at a rate of £2.50 per hour or received course credits for participating. All volunteers had normal or corrected-to-normal vision.

Apparatus

All the displays were generated and RTs collected on an IBM-compatible personal computer (Elonex plc., London, UK). The

displays were presented on a mono video graphics adapter (VGA) monitor. Participants responded via a conventional keyboard.

Stimuli

An example of the type of display used in the experiments can be found in Figure 2. The figure retains the exact spatial relationships between the elements as they appeared in the experiment; however the luminance relationships are not exactly as they appeared on the screen. The target was a vertically oriented pair of shapes and the distractors were horizontal pairs of shapes. For Experiments 1–4, the shapes could be either squares or circles; in Experiment 5 the elements were wedge shapes (more details are given later); in Experiment 6 diamond-shaped elements were used. In each experiment (except Experiment 5) the elements that made up the target or distractor were the same and so detection of the target was possible only when the two elements were grouped, enabling the orientation of the resulting bar to be detected. In all cases, when grouped the target comprised a vertical bar against horizontal distractors.

The search display contained one, three, five, or seven pairs of elements. These elements were presented randomly on a grid of positions on the screen. The grid had three positions horizontally and three positions vertically, and each location was separated by 3.6 cm with a flat noise function in both dimensions of ± 1.3 cm. The central location on the grid was not used as a possible location. This left eight possible positions for target or distractor. There was a 0.9 cm distance between the center of the two elements that made up the target or distractor. These parameters are set such that the between-pair separation was large in comparison with the within-pair separation.

Procedure

Participants sat approximately 0.5 m from the computer monitor in a semisoundproof room that was lit only by the light from the display. The task was to search for a target that was present on half the trials and absent on the remaining trials. A single trial commenced with a fixation cross presented centrally for 2,000 ms; this was replaced by the display that was itself replaced by the fixation cross as soon as a key response had been made. Participants were told to make a key response with one hand if the target was present

and another key response with their other hand if it was absent. In any one experiment half the participants responded "present" with their preferred hand and the other half responded "absent." Participants in all experiments were tested in all conditions and were presented with each display type 20 times. There was one practice block of 8 trials followed by two experimental blocks of 80 trials for each condition in the experiment, with display size manipulated randomly within each block.

Experiment 1

In Experiment 1, we examined visual search for targets and distractors consisting of pairs of circles to assess how search performance for such structures was affected by the polarity of the circles. In one condition, the circles in both target and distractors were the same contrast, both were brighter than the background (see Figure 2). In the other condition, within each target and distractor group the circles had opposite contrast polarity (one brighter and one darker, relative to the background, see Figure 3).

Method

The circles in all cases had a diameter of 0.6 cm. In both conditions the luminance of the background was kept constant and set at 21 cd/m^2 (as measured with a spot photometer, Salford Electronics Instrument, Salford, UK). In the light circles condition both the circles within target and distractor pairs were brighter than the background (27 cd/m^2). In the opposite polarity condition, one circle within each target or distractor pair was lighter than the background, this circle had the same luminance as circles in the light circles condition. The other circle in the pair was darker than the background (16 cd/m^2).

Participants

There were 12 participants (7 women and 5 men); 1 participant was left-handed and the remaining were right-handed.

Results

The mean RTs across all the participants are presented graphically in Figure 4. Descriptive statistics for the conditions are shown in Table 1. The main finding was clear: Search performance in the same polarity condition was relatively effective, with search slopes on the RT–display size function of 15 and 12 ms/item on present and absent displays. In contrast, performance was inefficient in the opposite polarity condition: The slopes for present and absent displays were 32 and 44 ms/item, respectively. These conclusions were confirmed by a three-way within-subjects analysis of variance (ANOVA) on the mean correct RTs per block. The variables were display size (one vs. three vs. five vs. seven item displays); condition (light circles vs. opposite polarity circles), and target (present vs. absent). There were main effects of display size, $F(3, 33) = 80.73$, $p < .001$; condition, $F(1, 11) = 30.95$, $p < .001$; and target, $F(1, 11) = 12.66$, $p < .01$. All the interactions were reliable: Target \times Display Size, $F(3, 33) = 4.46$, $p < .01$; Target \times Condition, $F(1, 11) = 11.17$, $p < .01$; Display Size \times

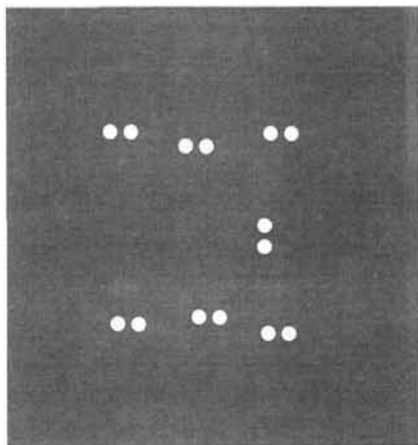


Figure 2. Example visual search display, Display Size 7, and target present.

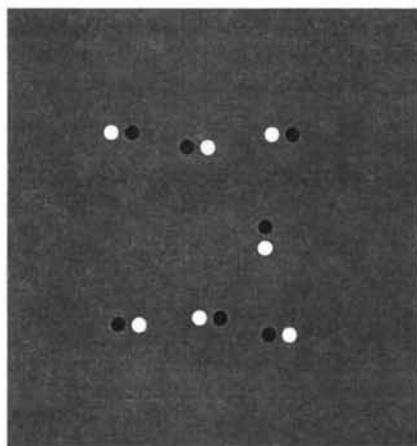


Figure 3. Example display used in Experiment 1: opposite polarity squares condition, Display Size 7, and target present.

Condition, $F(3, 33) = 15.43, p < .001$; and Display Size \times Target \times Condition, $F(3, 225) = 5.08, p < .01$. The three-way interaction was due to the effect of display size being more pronounced on the opposite than on the same polarity displays, and with these effects being larger on the absent than on the present displays. However, display size effects were larger on opposite than on same polarity displays even when present responses were analyzed alone, $F(3, 129) = 11.38, p < .001$. There was also a Display Size \times Condition interaction when Display Size 1 was excluded from the analysis, $F(2, 22) = 5.40, p < .05$. Error rates across all conditions were very low (overall mean: 4%), with no evidence for a speed-accuracy trade off.

Discussion

In the present study, participants had to group the elements within each stimulus in order to detect the target because the elements of the target and distractors were identical. The data demonstrate that the grouping necessary to distinguish targets from distractors could be carried out relatively efficiently when the elements had the same polarity of contrast because search slopes were relatively shallow and there was no indication that slopes on absent trials were twice those on present trials. Note also that the elements used here were small in comparison with the overall display area (the element to display area ratio was 1:180) so that the conditions were biased against finding very efficient search (see Duncan & Humphreys, 1989). The results in the same polarity condition are consistent with a parallel, if noisy, search process (cf. Humphreys & Müller, 1993) and are not consistent with a serial search account, in particular the present to absent slope ratio was 1:0.78.

In contrast to the results in the same polarity condition, search was relatively inefficient when the elements within the target and distractor groups had opposite contrast polarity. Slopes were then more than 30 ms/item on present trials, and the present to absent slope ratio was 1:1.38. Clearly,

performance was disrupted when the elements to be grouped had opposite contrast polarities. The search pattern in this condition is also more consistent with that expected by serial, self-terminating search (though see Humphreys & Müller 1993).

There are a number of possible reasons why search for opposite polarity circles was inefficient. One possibility is that grouping between these stimuli depends on the derivation of low spatial frequency components from the brightness values in the image (e.g., image blurring; Watt & Morgan, 1985). In this case grouping will be disrupted when the elements to be grouped have opposite contrast polarities. In the absence of grouping based on image blurring, the linking of local elements to form targets and distractors may depend on a slow and effortful scrutiny of local elements. We term this process *local linkage* to distinguish it from forms of grouping that appear to operate in parallel across wider areas of the image.

A second possibility is that grouping in parallel between the elements depends on absolute brightness levels, for instance, because it requires identical tokens representing surface properties of objects (cf. Marr, 1982). This process would have broken down in the opposite polarity condition because within-group elements differed in their absolute brightness levels (irrespective of their also having opposite contrast polarities).

A third possibility is that search became inefficient in the opposite polarity condition not because within-stimulus grouping was disrupted per se but because grouping between elements in targets and distractors was introduced (between-stimulus grouping). In the opposite polarity condition local elements in target and distractors had the same

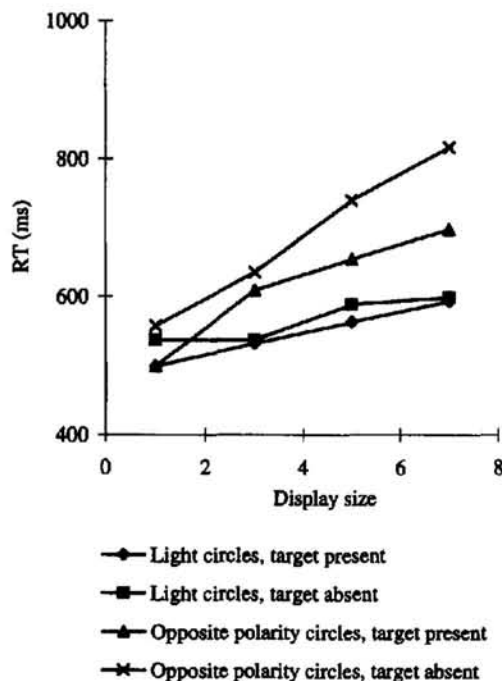


Figure 4. Mean reaction times (RTs) for Experiment 1.

Table 1
Summary Statistics for Experiments 1 and 2 Including
Least Squares Linear Fits

Condition	Intercept	Slope	95% CI ^a	r ²
Experiment 1				
Light circles				
Present	484	15.6	±5.2	1.00
Absent	517	12.1	±4.5	.86
Opposite polarity circles				
Present	486	32.2	±8.4	.94
Absent	510	44.3	±11.6	1.00
Experiment 2				
Opposite polarity circles				
Present	514	31.0	±5.4	.98
Absent	545	38.8	±6.9	.94
Darker circles				
Present	517	21.1	±4.0	1.00
Absent	538	26.4	±4.9	.94
Lighter circles				
Present	517	13.9	±2.9	.98
Absent	543	13.9	±2.9	.97

^a This is the 95% confidence interval for the search slope. It is based on the individual slope calculations for each participant and gives an indication of the spread of slopes within each condition across subjects.

token brightness values, whereas elements within targets and within distractors did not. This may have led to the similarity within the pairs of items that made up the stimuli being less than that between stimuli (this assumes that similarity was computed on the basis of the brightness values of individual element tokens). Grouping between elements in the target and distractors could even have competed with grouping between target elements, disrupting search.

We examined these different possibilities in Experiments 2 and 3. In Experiment 2, we tested whether performance was disrupted in the opposite polarity condition because within-group elements differed in their absolute brightness levels. The display contained within-group elements that were either the opposite polarity relative to the background (as in Experiment 1), or the absolute brightness levels of the within-group elements was maintained but the background brightness was varied to be either darker or lighter than the circle elements. If absolute brightness levels are important, then performance should be the same in all three conditions and search should be relatively inefficient. If absolute brightness levels are relatively unimportant but contrast polarity is important, then performance should be more efficient in the conditions in which within-group elements have the same polarity of contrast (both light or both dark) in comparison with when they have opposite polarities of contrast.

In Experiment 3, the relative magnitude of within-stimulus to between-stimulus grouping was evaluated by varying the distance between the target elements and the distractor elements.

Experiment 2

Method

There were three experimental conditions: opposite polarity circles, lighter circles, and darker circles. Across all conditions the physical luminance of the two circles that respectively made up the target and distractors was kept constant and the same as those used for the opposite polarity circles in Experiment 1 (16 cd/m² and 27 cd/m², respectively), with the background luminance being changed across conditions.

The opposite polarity condition was identical to that in Experiment 1. As before, the physical luminance of the background was between the luminance of the two circles: one circle was brighter than the background and the other circle was darker. The physical luminance of the background was set at 21 cd/m². In the second, lighter circles condition, the background brightness was set at 10 cd/m² so that both circles were brighter than the background. In the third, darker circles condition, the background brightness was set at 32 cd/m² so that the circles were darker than the background. The luminance relationships are illustrated in Figure 5.

Participants

There were 24 participants (13 women and 11 men); 2 participants were left-handed and the remaining were right-handed.

Results

The mean RTs are presented in Figure 6 and descriptive statistics for the conditions appear in Table 1. Inspection of Figure 6 suggests that search was relatively less efficient for

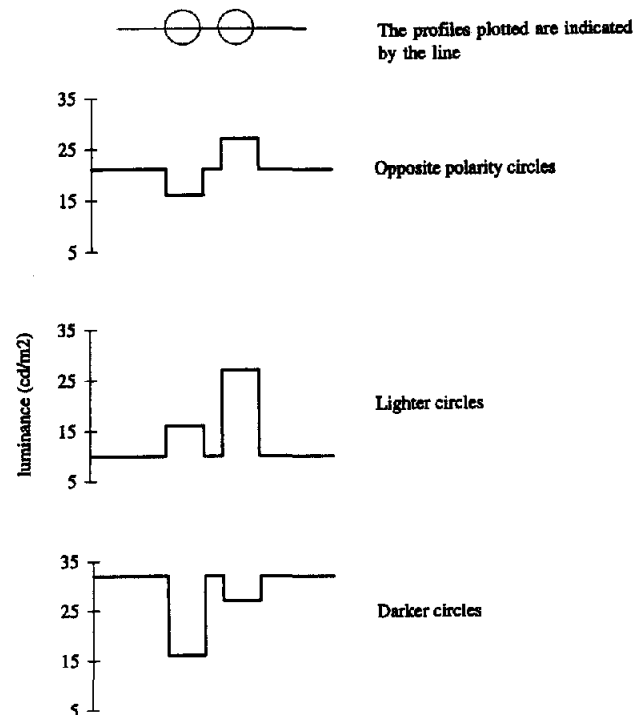


Figure 5. Luminance profiles for Experiment 2.

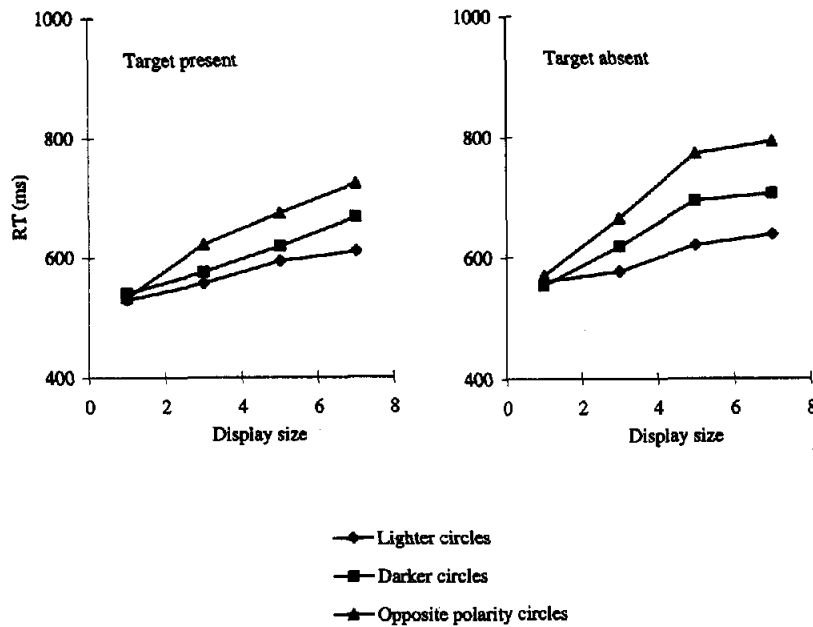


Figure 6. Mean reaction times (RTs) for Experiment 2.

the opposite contrast polarity circles than for circles with the same contrast polarity which differed in absolute brightness (both circles lighter or darker than the background). This was confirmed in a 4 (display size: one vs. three vs. five vs. seven) \times 3 (condition: lighter circles vs. darker circles vs. opposite polarity circles) \times 2 (target: present vs. absent) repeated measures ANOVA. There were main effects of display size, $F(3, 69) = 180.3, p < .001$; condition, $F(2, 46) = 24.87, p < .001$; and target presence, $F(1, 23) = 27.59, p < .001$. All the interactions were reliable: Target Presence \times Display Size, $F(3, 69) = 6.78, p < .001$; Target Presence \times Condition, $F(2, 46) = 8.93, p < .001$; Display Size \times Condition, $F(6, 138) = 21.49, p < .001$; and Display Size \times Target Presence \times Condition, $F(6, 714) = 2.25, p < .05$.

Comparison of the opposite polarity and the dark circles conditions showed a reliable Display Size \times Condition interaction, $F(3, 69) = 13.22, p < .001$. When Display Size 1 was removed there was still a main effect of condition, $F(1, 23) = 14.95, p < .001$; however, the Display Size \times Condition interaction just failed to reach significance, $F(2, 46) = 2.94, ns (p = .063)$, indicating that for Display Sizes 3, 5, and 7 there was a significant baseline increase in RTs and a trend for an accompanying increase in slope.

A similar comparison of the opposite polarity circles and the lighter circles conditions showed a reliable Display Size \times Condition interaction, $F(3, 69) = 35.26, p < .001$. When Display Size 1 was removed the interaction remained significant, $F(2, 46) = 11.83, p < .001$. In a comparison between the lighter circles and the darker circles conditions, there was also a reliable Display Size \times Condition interaction, $F(3, 69) = 10.91, p < .001$, which remained when Display Size 1 was removed, $F(2, 46) = 4.21, p < .05$. Search was most difficult with opposite polarity circles, and

the slopes for the search functions also tended to be steeper with these stimuli than with same polarity light or dark circles.

Error rates across the three conditions were again low (overall mean: 4%). However, errors were higher for the opposite polarity condition (5%) than for either the darker circles condition (3%) or the lighter circles condition (3%). For the opposite polarity circles condition, when the target was present, error rates increased with display size (from Display Size 1 to 7, the error rates were 5%, 5%, 5%, and 11%). Note that the increase in target misses in this condition could have artificially deflated the search function because increased errors would reflect participants responding before they had searched all the elements in the display. Nevertheless, errors followed the same trends as the RT data.

Discussion

Search was more efficient when the circles making up targets and distractors were the same contrast polarity than when they were opposite contrast polarities, even though the absolute brightness of the circles was kept constant. Slopes for the light circles condition were shallow: 13.9 ms/item for both target present and target absent, consistent with parallel (if somewhat noisy) search. Slopes for the darker circles condition were steeper (target present: 21.1 ms/item; target absent: 26.4 ms/item), suggesting the introduction of a serial component in search, an argument supported by the ratio of the target present to target absent slopes (1:1.25). However, slopes for the opposite polarity circles were even steeper (target present: 31.0 ms/item; target absent: 38.8 ms/item) and the slope ratio again suggested that there was a serial component in search (1:1.25).

However some details require comment. If Display Size 1 is excluded from a comparison between the darker circles condition and the opposite polarity circles condition, then there was only a trend for a Display Size \times Condition interaction. There are two points worth making here. First, there was still a highly reliable effect of condition: Opposite polarity circles were more difficult to group than darker circles. Second, the single item is an important measure of basic discriminability in visual search (see Triesman & Gelade, 1980). The difference in slope between conditions from Display Size 1 to Display Size 3 provides the most useful measure of the degree to which the target can be detected in parallel, as it disentangles the discriminability of the target (as measured by Display Size 1) and the effects of introducing other items.

This experiment also showed a significant difference between search for same polarity dark items and same polarity light items; RTs were slower and search slopes steeper for the same polarity darker items. Such results suggest that same polarity darker items were apparently more difficult to group. This observation was irrelevant to our main interests, therefore it was not investigated further. However, one possible explanation assumes that the image blurring mechanism is not dependent on the luminance of items but on the contrast between them. There are many measures of contrast and it still remains unclear which measures model the range of experimental data most closely. The appropriate measure may depend on the type of stimuli and the nature of the task (Alexander, Xie, & Derlacki, 1993; Burkhardt, Gottesman, Kersten, & Legge, 1987; Legge & Kersten, 1983). However, on a range of indexes the lighter of the two circles in the darker circles condition also had clearly lower contrast. For example, when we used Weber contrast, this circle had a contrast of 0.16,¹ far lower than any of the other circles in the experiment (range: 0.24 to 1.70). After blurring, the resulting descriptions of target and distractor may not have always been sufficiently dark to enable a vertical bar to be perceived relative to the gray background. However, although this factor may account for the difference between the same polarity conditions it cannot account for the further cost associated with a switch in polarity between the two items to be grouped. We can think of this last result in two ways: either the circles were grouped on the basis of categorical brightness descriptions of each token (light or dark), or by image blurring, provided there was sufficient contrast to perceive the circles relative to the gray background. In either case, grouping should be strongly disrupted when the circles have opposite contrast polarities.

Experiment 3

In Experiment 3 we varied the spacing between targets and distractors while keeping the separation within target and distractor groups constant. The ratio of the distance between the stimuli relative to the size of the stimuli (taking pairs of circles together) varied from 1:2.2 to 1:4.4, and the ratio of the overall display area relative to the size of the individual stimuli varied from 1:100 to 1:250 (note this

comparison is made relative to the area of a single circle, not a pair). The magnitude of these distances should be sufficient to produce severe disruption to target-distractor grouping. Duncan and Humphreys (1989) showed that target-distractor grouping was efficient only when the ratio of the stimuli size to the total display area was about 1:3.²

Zucker and Davis (1988) varied the ratio between the size and spacing of rows of dots and examined their perceptual equivalence to a line. They found that rows of dots generated the same illusory brightening as a solid line in the center of the sun illusion when the dots had a size to spacing ratio of 1:3. With size to spacing ratios between 1:3 and 1:5, the illusion broke down and disappeared with size to spacing ratios of 1:6. The size to spacing ratios between individual circles within a target or distractor pair here was 1:0.5, and that between circles in different pairs varied from 1:2.2 to 1:4.4, a range over which, if between-item interference is important, grouping of this kind should start to break down.

Method

The light circles and the opposite polarity conditions were repeated. However, unlike Experiment 1, display size was kept constant at seven pairs of circles. The spacing between the circles that made up each target and distractor was kept constant at the separation that had been used for the previous two experiments. The spacing between the pairs of circles was varied, and the following six different values of separation were tested: 2.2, 2.6, 3.1, 3.5, 3.9, and 4.4.

Figures 7 and 8 show two example displays to illustrate this range. Figure 7 shows a display with an average size to spacing ratio of 2.2. Figure 8 shows a display with an average size to spacing ratio of 4.4.

Participants

There were 10 participants (4 women and 6 men); 1 participant was left-handed and the remaining were right-handed.

Results

Mean RTs across participants are presented in Figure 9 and were analyzed in a 6 (spacing ratio: 2.21 vs. 2.64 vs. 3.07 vs. 3.50 vs. 3.93 vs. 4.35) \times 2 (condition: light circles vs. mixed polarity circles) \times 2 (target: present vs. absent) repeated measures ANOVA. There were main effects of

¹ Weber contrast is calculated as the change in luminance divided by the background luminance.

² One caveat here is that Duncan and Humphreys (1989) used stimuli composed of two line orientations (L figures) and we used stimuli that formed simple lines. It is possible that grouping between single lines may operate across larger element size to display area ratios than grouping between L figures. Nevertheless, previous research with single line stimuli in search tasks suggested that local interactions are important for grouping between distractors (Bacon & Egeth, 1991; Sagi & Julesz, 1987). The large element size to display area ratios here should produce marked disruption in such local grouping processes.

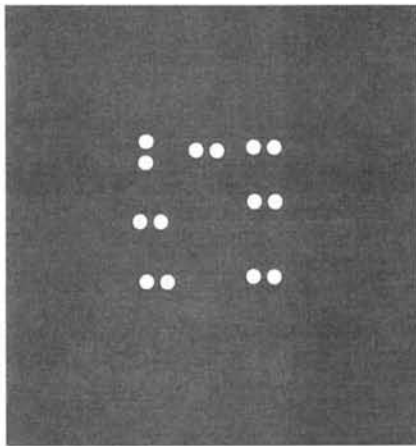


Figure 7. Example display showing the minimum spacing ratio used in Experiment 3.

condition, $F(1, 9) = 30.07$, $p < .001$, and target, $F(1, 9) = 30.51$, $p < .001$, but no effect of spacing ratio, $F(5, 45) = 0.87$, ns . Two interactions were reliable: Target \times Spacing Ratio, $F(5, 45) = 3.19$, $p < .05$, and Target \times Condition, $F(2, 9) = 26.95$, $p < .001$. Separate analysis of the target present and absent data revealed the following: For target present there was a reliable main effect of the spacing ratio, $F(5, 45) = 4.40$, $p < .01$. However, there was no reliable effect of spacing ratio for absent trials, $F(5, 45) = 0.76$, ns . The means for target present responses as the spacing ratio increased were 738, 721, 689, 688, 710, and 718 ms. The shortest RTs were found at the spacing ratio used for Experiments 1 and 2 (3.5: RT = 688 ms), with longer RTs at both wider and the closer spacings. This trend was confirmed by planned comparisons between the 3.5 spacing ratio and the other five spacing ratios: 2.2 spacing ratio (50-ms increase), $t(10) = 3.09$, $p < .05$; 2.6 spacing ratio (33-ms increase), $t(10) = 2.29$, $p < .05$; 3.1 spacing ratio (1-ms increase), $t(10) = 0.05$, ns ; 3.9 spacing ratio (22-ms increase), $t(10) = 1.64$, ns ; 4.4 spacing ratio (30-ms increase), $t(10) = 2.59$, $p < .05$. Importantly, this effect of the spacing ratio on present trials did not interact with the conditions, $F(9, 165) = 1.01$, ns . The error rates for each condition were low (overall mean error rate: 4%), and there was no sign of a speed-accuracy trade off.

Discussion

There was no interaction between the display condition (light circles vs. opposite polarity circles) and the ratio between the size of the stimuli and the spacing between target and distractor pairs. Thus the factor responsible for the advantage of the same polarity over the opposite polarity displays appears to be constant across very wide variations in target-distractor spacing. This suggests that the relatively poor performance with opposite polarity displays is not caused by grouping between the circles in the target and distractor that have the same polarity. By elimination, we suggest that the targets were difficult to detect in opposite

polarity displays because the component elements making up each shape were hard to group. This is consistent with an account of grouping based on sampling low spatial frequency components (image blurring) or comparison of the local categorical token representations (light vs. dark).

Although there was no interaction between spacing and the display condition, there was an overall effect of spacing on present responses. One reason for this effect is that target distractor spacing here covaried with absolute display area. At the larger size to spacing ratios, targets and distractors were presented more peripherally. Thus the decrease in efficiency for detecting the target may reflect decreased acuity. However, note that this factor (if operating) had no effect on absent responses. The effect on present responses, with both same and opposite polarity circles, suggests that participants made use of peripheral information to help guide search rather than search being strictly serial; the accuracy of this guidance process may decrease with reduced acuity. This guidance of search may also be more efficient when the elements within targets group more strongly (with same rather than opposite polarity circles).

The account of grouping based on blurring the local circles in Experiments 1-3 predicts that performance should not be greatly affected by substituting squares for the local circles that make up the target and distractor. Blurring should produce grouping of local shapes with the same contrast polarities, as well as difficulties in grouping local shapes with opposite polarities, irrespective of whether the local shapes do or do not contain oriented edge information. Conversely, the presence of collinear edges in the squares may enable grouping to be based on output from local, orientation tuned filters (cf. Grossberg & Mingolla, 1985). Also, according to accounts such as those produced by Grossberg and his colleagues (Grossberg & Mingolla, 1985; Grossberg & Todorovic, 1988), grouping between orientation-tuned filters may be unaffected by the polarity of the changes in contrast at the edges. Grossberg and Mingolla (1985), for example, proposed that grouping by collinearity operates within a boundary contour system

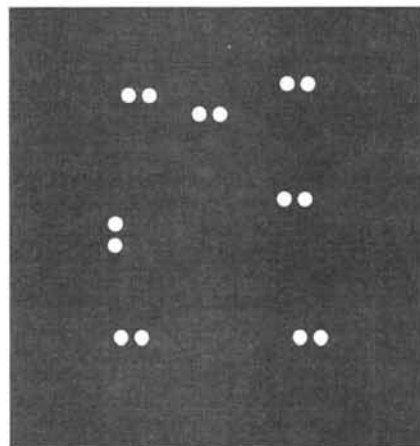


Figure 8. Example display showing the maximum spacing ratio used in Experiment 3.

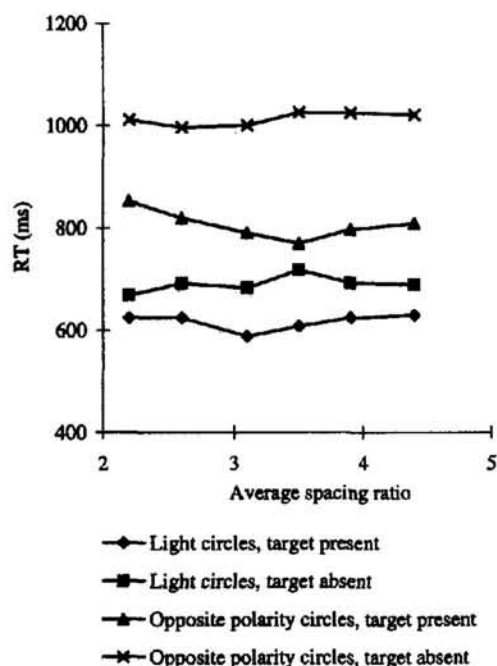


Figure 9. Mean reaction times (RTs) for Experiment 3.

(BCS) that operates with unsigned edge information. This BCS provides input to a separate feature contour system (FCS) that is sensitive to surface brightness and that acts to fill in regions between bounded contours specified by the BCS. It follows that, in contrast to the effects of contrast polarity observed with local circles, there may be relatively small effects of contrast polarity on search with local squares. This prediction is examined in Experiment 4.

Experiment 4 was conducted in two parts. In Experiment 4a we compare performance with targets and distractors formed from pairs of local circles, pairs of local squares, and a solid bar. In this experiment the elements always had the same contrast polarity and were lighter than the background. In this subexperiment, we tested (a) whether there were any overall differences in processing efficiency when squares replaced the local circles, and (b) how performance varied overall when targets and distractors were formed from local elements that had to be grouped relative to when local grouping was not necessary (with solid bars). Experiment 4b compared performance with stimuli made from local squares and local circles that had opposite contrast polarities. This tests whether the effects of contrast polarity we have observed with local circles is reduced or even eliminated when grouping can operate on collinear edges (with local squares).

Experiment 4a

Method

Targets and distractors were either solid bars (differing by 90°), pairs of circles, or pairs of squares. The pairs of squares were equivalent to the solid bar but with a central section removed (see

Figure 10 for an example display). The area of the squares was the same as the circles (0.3 cm^2 as in Experiments 1–3). The stimuli all had the same brightness (27 cd/m^2) and were brighter than the background.

Participants

There were 10 participants (7 women and 3 men); all were right-handed.

Results

The mean correct RTs are shown in Figure 11. Descriptive statistics for this experiment are given in Table 2. In general the slopes for the three conditions were shallow (target present: 6.2, 10.8, and 17.5 ms/item; target absent: 11.9, 21.5, and 25.4 ms/item, for the solid light bar, light circles, light squares conditions, respectively). The mean correct RTs per block were analyzed in a 4 (display size: 1 vs. 3 vs. 5 vs. 7) \times 3 (condition: bar vs. pair of squares vs. pair of circles) \times 2 (target: present vs. absent) ANOVA. There were reliable main effects of display size, $F(3, 27) = 19.45$, $p < .001$; condition, $F(2, 18) = 10.02$, $p < .001$; and target, $F(1, 9) = 9.77$, $p < .05$. The following interactions were reliable: Target \times Display Size, $F(3, 27) = 4.17$, $p < .05$, and Display Size \times Condition, $F(6, 54) = 9.94$, $p < .001$. This last interaction remains reliable even if Display Size 1 is removed, $F(4, 36) = 9.81$, $p < .001$.

Separate analysis of the interactions revealed the following: The trend for faster RTs to pairs of squares relative to pairs of circles was not significant: target present, $F(1, 9) = 0.61$, *ns*; absent trials, $F(1, 9) = 1.73$, *ns*; and there were no significant Display Size \times Condition interactions: target present, $F(3, 107) = 1.62$, *ns*; target absent, $F(3, 107) = 0.85$, *ns*. Performance with the solid bar stimuli was faster than with the pair of squares for target present trials, $F(1, 9) = 8.33$, $p < .05$. For target absent trials there was a significant Display Size \times Condition interaction, $F(3,$

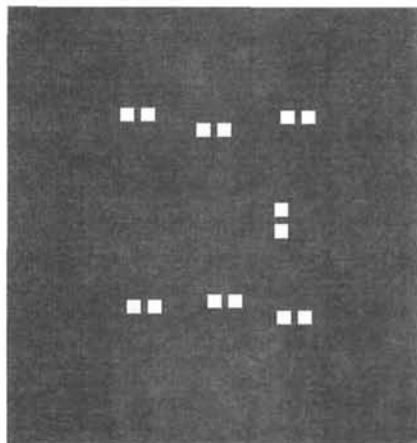


Figure 10. Example display used in Experiment 4a: same polarity squares condition, Display Size 7, and target present.

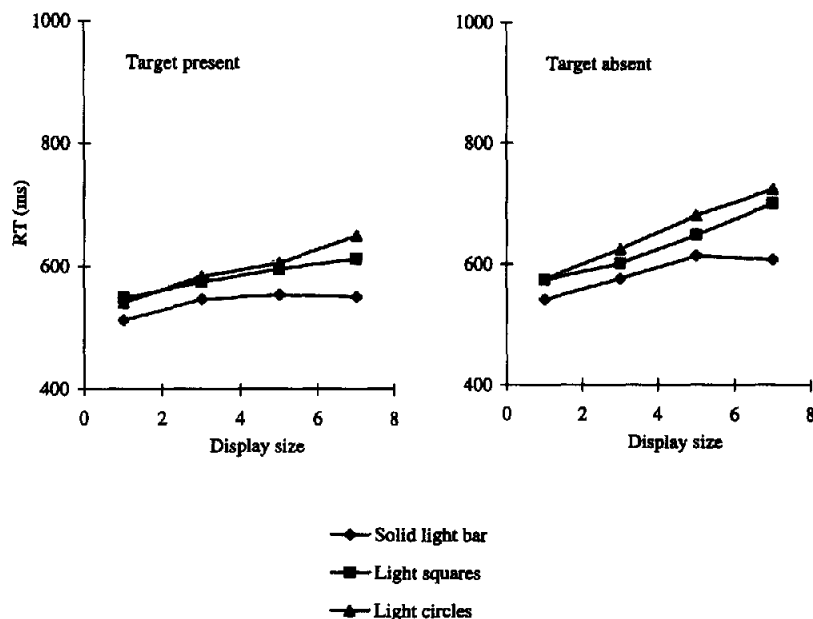


Figure 11. Mean reaction times (RTs) for Experiment 4a.

107) = 4.76, $p < .01$. Display size effects were larger for pairs of squares than for solid bars.

Error rates were low overall ($M = 2\%$) and there was no clear evidence of a speed–error trade-off.

Experiment 4b

Method

There were two conditions: Targets and distractors were formed from either local squares (Figure 12) or local circles (Figure 3), and the stimuli making up each pair always had opposite contrast polarities (luminance values were set as in Experiment 1).

Participants

There were 12 participants (4 women and 8 men); 2 participants were left-handed and the remaining were right-handed.

Results

The mean correct RTs are presented in Figure 13. Descriptive statistics are shown in Table 2. The slopes for the mixed polarity circles were steeper (target present: 32.9 ms/item; target absent: 32.3 ms/item) than for the mixed polarity squares (target present: 12.4 ms/item; target absent: 20.7 ms/item), with the biggest difference being between the slopes on target present trials. These conclusions are confirmed by a 4 (display size: 1 vs. 3 vs. 5 vs. 7) \times 2 (condition: mixed polarity squares vs. mixed polarity circles) \times 2 (target: present vs. absent) ANOVA. There were main effects of display size, $F(3, 33) = 31.07$, $p < .001$; condition, $F(1, 11) = 15.60$, $p < .01$; and target, $F(1, 11) = 11.81$, $p < .01$. One interaction was reliable: Display Size \times

Condition, $F(3, 33) = 12.96$, $p < .001$, even if Display Size 1 was removed, $F(2, 22) = 4.46$, $p < .05$. The effects of display size were larger on opposite polarity circles than on opposite polarity squares.

Error rates for each condition were low (overall rate: 4%), and there was no systematic pattern across conditions. There was no evidence of a speed–error trade off.

We carried out two further analyses to compare performance across Experiments 4a and 4b. The first analysis compared opposite polarity circles with same polarity circles. There were main effects of target, $F(1, 20) = 15.29$, $p < .001$; display size, $F(3, 60) = 46.55$, $p < .001$; and a Display Size \times Polarity interaction, $F(3, 60) = 6.16$, $p < .001$ (replicating the effects from Experiment 1).

The second analysis compared opposite polarity squares with same polarity squares. There were main effects of target, $F(1, 20) = 23.02$, $p < .001$; display size, $F(3, 60) = 33.70$, $p < .001$; and a Display Size \times Target interaction, $F(3, 60) = 4.45$, $p < .01$. Importantly, there was no main effect of opposite versus same polarity squares, and there was no interaction with this factor.

Discussion

Search was disrupted by a polarity difference between the items to be grouped only when the items had no collinear edges. For target present responses, the slope for opposite polarity circles was steep (33 ms/item) when compared with same polarity circles (18 ms/item), and target absent responses showed the same difference (opposite polarity circles 32 ms/item, same polarity circles 25 ms/item). However, for pairs of squares the polarity of the squares did not produce the same large significant difference in the search

Table 2
Summary Statistics for Experiments 4a, 4b, 5, and 6
Including Least Squares Linear Fits

Condition	Intercept	Slope	95% CI ^a	r ²
Experiment 4a				
Solid light bar				
Present	516	6.2	±4.1	.67
Absent	537	11.9	±6.3	.84
Light squares				
Present	540	10.8	±4.4	.99
Absent	545	21.5	±10.7	.98
Light circles				
Present	540	17.5	±8.5	.99
Absent	550	25.4	±11.1	1.00
Experiment 4b				
Opposite polarity circles				
Present	513	32.9	±10.1	.99
Absent	550	32.3	±9.8	.96
Opposite polarity squares				
Present	542	12.4	±7.2	.93
Absent	537	20.7	±7.8	.94
Experiment 5				
Light elements				
Present	516	6.12	±4.3	.78
Absent	559	3.89	±4.2	.63
Opposite polarity elements				
Present	502	10.6	±4.7	.92
Absent	564	6.05	±5.1	.60
Single element				
Present	539	56.9	±14.5	.98
Absent	538	109	±21.5	1.00
Experiment 6				
Light circles				
Present	529	9.18	±4.9	.94
Absent	544	10.2	±7.4	.96
Light diamonds				
Present	522	17.4	±7.4	.99
Absent	562	18.1	±9.8	.99
Opposite polarity circles				
Present	549	32.9	±9.1	.93
Absent	564	41.3	±12.9	.97

^a This is the 95% confidence interval for the search slope. It is based on the individual slope calculations for each participant and gives an indication of the spread of slopes within each condition across subjects.

slope (11 ms/item vs. 18 ms/item for target present and 22 ms/item vs. 25 ms/item for target absent). Overall search slopes were relatively shallow when either the brightness of the items was the same or collinear edge information was present. It is interesting to note that when both of these grouping features were present (with same polarity squares), search slopes did not decrease significantly, relative to the baseline provided by the same polarity circles condition and the opposite polarity squares condition. Nevertheless the search slopes when both grouping features were present (with same polarity squares) were greater than when no grouping was needed to detect the target (in the solid bar condition).

As noted before, a model of grouping that relies simply on low spatial frequency sampling of the image would predict no advantage for light squares compared with light

circles, as both shapes have similar low spatial frequency characteristics. Consequently, this model would also predict no difference between the grouping of reverse polarity circles and the grouping of reverse polarity squares. Models of grouping that rely on the representation of shape tokens fare no better in trying to explain the pattern of data. This kind of model would also predict that replacing the circles with squares in the opposite polarity case would not facilitate grouping of the items.

Overall the data suggest the existence of two separate grouping processes, one based on edges and one based on brightness information. Edge-based grouping is revealed by the contrast in performance with opposite polarity squares and opposite polarity circles. Brightness-based grouping (involving either blurring or token matching) is revealed by the contrast in performance between same and opposite polarity circles. The fact that performance is no more efficient when both mechanisms are available (with same polarity squares) than when only one is available (with same polarity circles and with opposite polarity squares, respectively) constrains our interpretation of how the two grouping processes operate. We return to this point in the General Discussion.

However one possible confound remains. In the opposite polarity squares condition it is possible that the pairs of squares are not grouped and instead participants use a local feature formed from the horizontal internal contour between the two elements in the target. In distractors this contour is vertical. Target detection may be based on the presence of this simple feature regardless of whether the items can be grouped or not.

Experiment 5 was a control experiment designed to test whether grouping of opposite polarity elements with collinear edges occurs in parallel, even when local cues are not present to distinguish targets from distractors. In Experiment 5, targets and distractors had the same internal contour (at 45°, running from top right to bottom left), and the orientation of this contour did not provide any cue to the presence of the target. There were three conditions. In

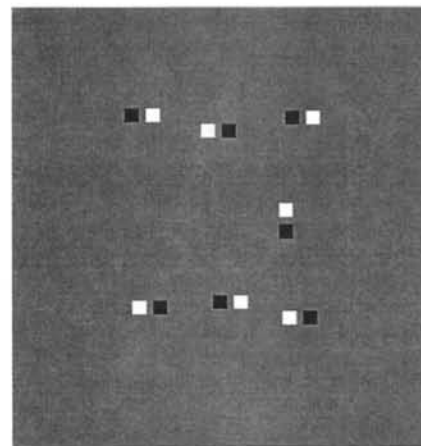


Figure 12. Example display used in Experiment 4b: opposite polarity squares condition, Display Size 7, and target present.

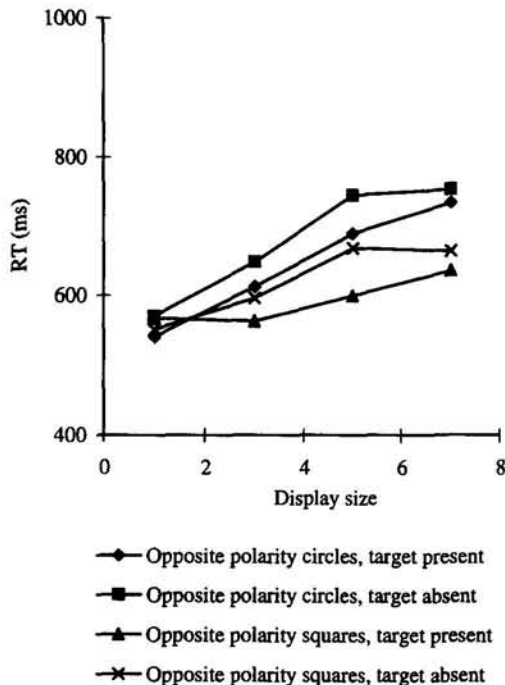


Figure 13. Mean reaction times (RTs) for Experiment 4b.

the first condition, the two parts that made up the bar were both light; in the second condition, the two parts had opposite contrast polarity. In the third condition participants had to search for an individual element. This was a control to assess whether participants could detect the target on the basis of the small shape difference between the elements that made up the target and the distractors.

Experiment 5

Method

There were three conditions. In two of the conditions, targets and distractors consisted of pairs of shapes arranged to form a solid bar with a central 45° stripe deleted. The target was made from a vertical bar and the distractors were made from horizontal bars. The overall dimensions of the stimuli were the same as the solid bars in Experiment 4a. In the light segments condition, both elements were brighter than the background (27 cd/m²). In the opposite polarity segments condition, one segment was lighter than the background (27 cd/m²) and the other was darker (16 cd/m²; see Figure 14 for an example display). In the third condition, all elements were lighter than background, the target consisted of a single segment that had a vertically oriented point and the distractors had horizontally oriented points (see Figure 15 for an example display). In all three conditions the background brightness was the same (21 cd/m²).

Participants

There were 12 participants (8 women and 4 men), who were all right-handed.

Results

The mean RTs are presented in Figure 16 and descriptive statistics for each condition appear in Table 2. The results are clear; regardless of the polarity of the items, search for the paired elements is efficient and relatively independent of display size. This contrasts with search for a single element, which gave very steep search functions. This was confirmed in a 4 (display size: 1 vs. 3 vs. 5 vs. 7) × 3 (condition: light element vs. opposite polarity elements vs. single element) × 2 (target: present vs. absent) repeated measures ANOVA. There were reliable main effects of display size, $F(3, 33) = 72.65, p < .001$; condition, $F(2, 22) = 67.02, p < .001$; and target presence, $F(1, 11) = 67.38, p < .001$. All the interactions were reliable: Display Size × Condition, $F(6, 66) = 61.97, p < .001$; Target Presence × Display Size, $F(3, 33) = 12.2, p < .001$; Target Presence × Condition, $F(2, 22) = p < .001$; and Target Presence × Display Size × Condition, $F(6, 354) = 12.63, p < .001$.

Comparison of the opposite polarity segments and the same polarity elements showed no main effect of condition, $F(1, 11) = 0.31, ns$, and no reliable Display Size × Condition interaction, $F(3, 33) = 2.08, ns$. A comparison between same polarity elements and the single element condition showed a reliable Display Size × Condition interaction for both target present, $F(3, 129) = 24.52, p < .001$, and target absent, $F(3, 129) = 81.77, p < .001$. Similarly, a comparison between opposite polarity elements and single element conditions also showed a reliable Display Size × Condition interaction for both target present, $F(3, 129) = 20.43, p < .001$, and target absent, $F(3, 129) = 74.66, p < .001$. Performance was particularly inefficient in the single element condition.

Discussion

Search was efficient and appeared to occur in parallel for both same polarity segments (target present: 6 ms/item; target absent: 4 ms/item) and for opposite polarity segments

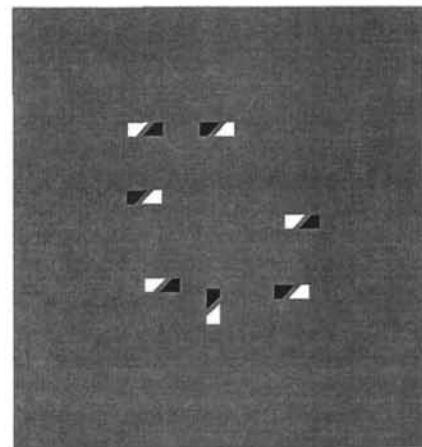


Figure 14. Example display used in Experiment 5: opposite polarity elements condition, Display Size 7, and target present.

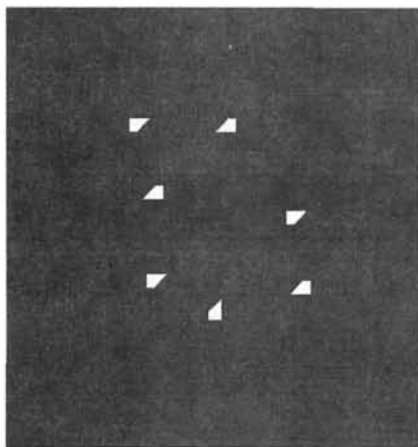


Figure 15. Example display used in Experiment 5: single element condition, Display Size 7, and target present (the target is the element with the upward point, bottom row in the middle.)

(target present: 11 ms/item; target absent: 6 ms/item). This efficient search was not simply due to the elements comprising targets and distractors being very discriminable; performance in the single element control condition was slow and very dependent on the display size (target present: 57 ms/item; target absent: 109 ms/item).

This experiment demonstrates two points. First, the grouping of reverse polarity items in Experiment 4b is not a result of the introduction of a horizontal contour to the target between the two squares. Grouping of opposite polarity items with collinear edges is still efficient even when the internal contour (the contour between the two elements) is the same in targets and distractors. Second, it is clear that,

providing collinear contours are present, grouping is relatively insensitive to the polarity of the items within the group.

Relative to when the square elements were used in Experiment 4, search for the present stimuli was yet more efficient. This is surprising as, in both cases, the same grouping features were present. One possible explanation is that grouping between squares is actually impaired by the internal contour. The horizontal internal contour forms a T junction with the external contour made by the collinear edges. The T junction provides an important cue for segmenting the visual scene because such a junction tends to occur at the boundary of surfaces (see Enns & Rensink, 1991). Such a cue may disrupt grouping between the elements. A T junction was not present in the wedge elements used here, and grouping would hence be less inhibited.

Although the present data show that grouping between collinear edges is relatively insensitive to contrast polarity, it remains unclear how the presence of collinear edges mitigates effects due to the polarity of the elements. There is a great deal of evidence that activity in a high spatial frequency channel can mask information in a low spatial frequency channel (Stromeyer & Julesz, 1972; Henning, Hertz, & Broadbent 1975; Julesz, 1980). The presence of the edge information (in the squares or wedges) provides a stronger high spatial frequency signal than that present for circles. It is possible that masking from high spatial frequency components generates the insensitivity to the polarity of contrast. In a low spatial frequency channel two opposite polarity elements do not provide a strong oriented signal (they cannot be blurred together). Masking of this channel, by high spatial frequencies, may then lead to search becoming relatively efficient.

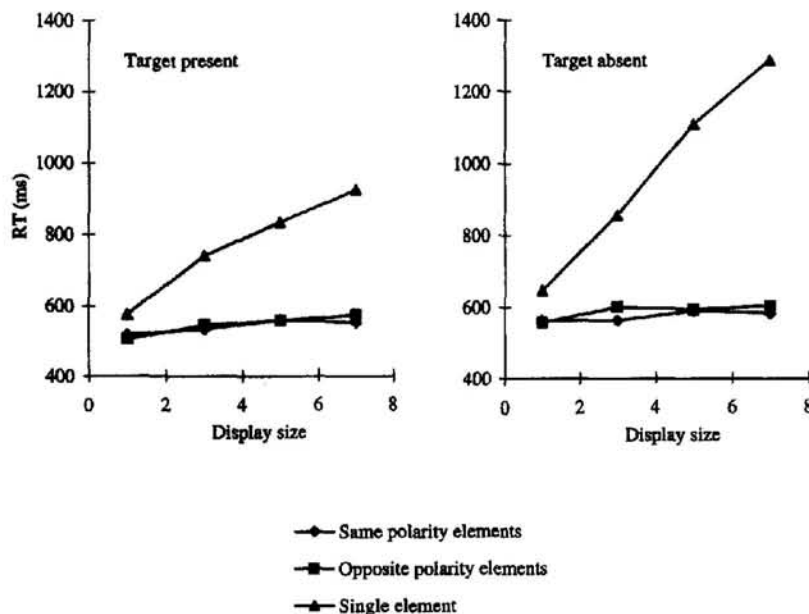


Figure 16. Mean reaction times (RTs) for Experiment 5.

To test the above account, in Experiment 6 we investigated grouping between pairs of items that had the same strong high spatial frequency signal as squares but did not have collinear edges—pairs of diamonds. If the presence of the edges alone masks grouping by blurring, then a pair of light diamonds should be difficult to group; search performance should be inefficient relative to a baseline where grouping by blurring is possible (e.g., with pairs of light circles). This prediction was evaluated in Experiment 6. Search for vertically oriented pairs of diamonds was compared with two baseline conditions: pairs of light circles and pairs of opposite polarity circles. Light circles should group by image blurring and so provide a marker of performance when that process operates. Opposite polarity circles may only group by what we have termed a process of *local-linkage*. This condition provides a marker of performance when only this grouping process operates.

Experiment 6

Method

There were three conditions: light circles, opposite polarity circles, and light diamonds. The first two conditions were exactly the same as in Experiment 1. The third condition consisted of pairs of light diamonds (squares rotated through 24°). The diamonds had the same luminance as the circles. An example display is shown in Figure 17.

Participants

There were 12 participants (8 women and 4 men); 2 participants were left-handed and the remaining were right-handed.

Results

The mean RTs are presented in Figure 18 and descriptive statistics for the conditions appear in Table 2. Inspection of Figure 18 suggests that search was least efficient for the

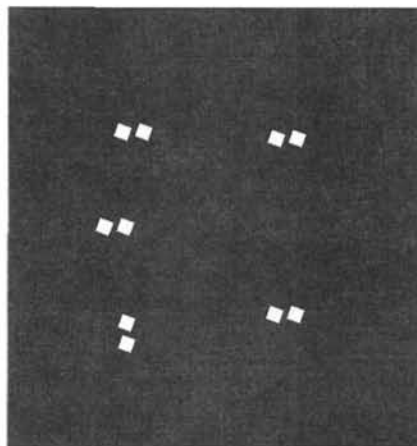


Figure 17. Example display used in Experiment 6: light diamond condition, Display Size 5, and target present.

opposite contrast polarity circles and most efficient for light circles. Search for light diamonds was slightly less efficient than for light circles but markedly more efficient than for opposite polarity circles, especially for target present. In a 4 (display size: 1 vs. 3 vs. 5 vs. 7) \times 3 (condition: lighter circles vs. light diamonds vs. opposite polarity circles) \times 2 (target: present vs. absent) repeated measures ANOVA, there were reliable main effects of display size, $F(3, 33) = 36.01, p < .001$; condition, $F(2, 22) = 17.25, p < .001$; and target presence, $F(1, 11) = 9.12, p < .05$. Only one interaction was reliable: Display Size \times Condition, $F(6, 66) = 12.59, p < .001$ [excluding Display Size 1, $F(4, 44) = 2.65, p < .05$].

Comparison of the opposite polarity circles and the same polarity diamonds showed a reliable Display Size \times Condition interaction, $F(3, 33) = 18.41, p < .001$. In a similar comparison of the light circles and light diamonds conditions there was no main effect of condition, $F(1, 11) = 2.5, ns$ ($p = .142$), though there was a weak trend toward a Display Size \times Condition interaction, $F(3, 33) = 2.46, ns$ ($p = .08$). Finally, a comparison between the opposite polarity circles and light circles conditions showed a reliable Display Size \times Condition interaction, $F(3, 33) = 14.8, p < .001$ (replicating the results in Experiment 1). Display size effects were larger with opposite polarity circles than with either light circles or light diamonds.

Discussion

The presence of noncollinear edge information caused interference in but did not block the brightness grouping mechanism. Search slopes for pairs of light circles were shallow (9 and 10 ms/item for target present and absent, respectively), and the target present to target absent slope ratio (1:1.1) is more consistent with parallel search than with serial self-terminating search (which, as noted before, produces slope ratios closer to 1:2). The introduction of noncollinear edge information in the light diamonds condition produced (nonreliable) steeper search slopes relative to the light circles condition (17 and 18 ms/item for target present and target absent). This is consistent with the edges in the diamonds disrupting grouping by blurring (measured in the light circles condition). However, the effect was not strong, and it was not large enough to account for the difference produced by altering contrast polarity between the circles to be grouped. This evidence suggests that the presence of edge information alone (noncollinear edges) does not block the action of the brightness grouping process. By elimination then, we argue that the presence of collinear edges cannot block the signal that encodes the brightness values associated with the squares. Thus, the differences in contrast polarity between the opposite polarity squares should not be blocked by the presence of the edges but should remain encoded (minimizing grouping by blurring when stimuli have opposite contrast polarities). Rather than the presence of edge information masking the low spatial frequency signal, the data suggest that grouping with squares and wedges was based on independent edge representations that are nonsigned for their direction of contrast.

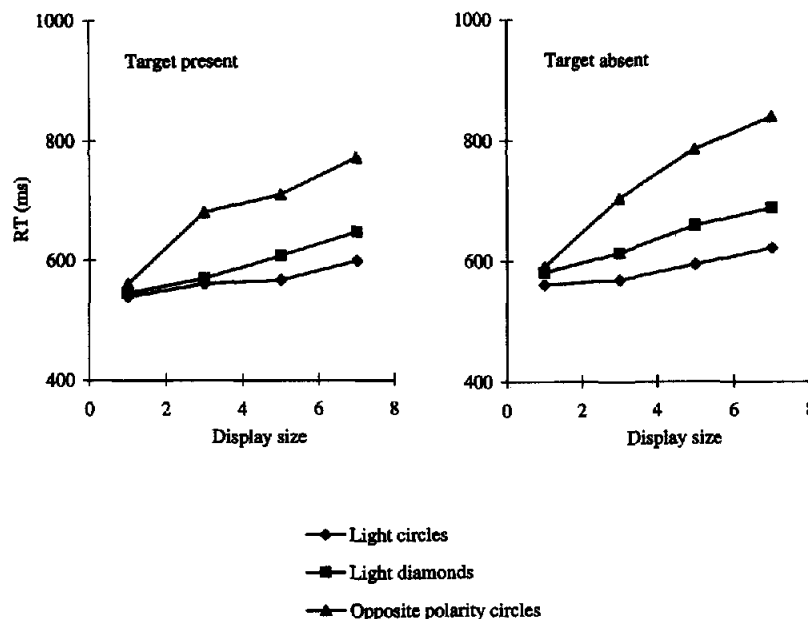


Figure 18. Mean reaction times (RTs) for Experiment 6.

General Discussion

We have shown that grouping by brightness is disrupted by a polarity difference between the items to be grouped (Experiment 1). This effect was not due to brightness differences alone (Experiment 2) and appeared not to be due to the introduction of alternative groupings forming between circles from different pairs (Experiment 3). In contrast, differences in brightness polarity were not disruptive when the stimuli to be grouped had collinear edges (Experiments 4 and 5). Apparently grouping based on collinearity is not sensitive to the polarity of brightness contrast. The qualitatively different effects of brightness polarity on grouping with and without edge information (with local squares, wedges, and circles) suggest that grouping based on brightness and grouping based on edges are mediated by two separate processes. This difference was found not to be due simply to a masking of the brightness information by the presence of edges (Experiment 6).

When either edge information was present (with squares) or the within-pair brightness values had the same polarity (with same polarity circles), we propose that search was spatially parallel (if somewhat noisy). Search rates were typically of the order of 12–15 ms/item, and present to absent slope ratios were roughly equal. These experiments then add to the growing body of experimental evidence suggesting that complex relations between image features can be computed in parallel (e.g., Donnelly et al., 1991; Elder & Zucker, 1993; Enns, 1990; Enns & Rensink, 1991; Ramachandran, 1988). These data do not support accounts such as feature integration theory (Triesman & Gelade, 1980), which holds that even the most simple feature combination process (e.g., to combine color and orientation, or even two form elements together) cannot be accomplished

in parallel. The data also weigh against accounts of search that rely on the parallel computation of only simple similarity relationships (Duncan & Humphreys, 1989). The property of collinearity between edge segments seems to be computed in parallel across images. Such properties are, of course, good candidates for assembling local image features into descriptions of coherent, three-dimensional objects because they likely reflect real objects rather than accidental image features (Biederman, 1987; Lowe, 1987). Parallel computation of collinear edges (within the limits of acuity) will enable rich (if noisy) image descriptions to be derived rapidly; such “quick and dirty” image descriptions may be necessary to direct action in the real world (see Enns & Rensink, 1991).

We have used two contrasting sets of findings, when different displays were compared, to argue for the involvement of two grouping mechanisms in early, preattentive (spatially parallel) vision. First, the contrast between the effects of introducing opposite polarity elements into target and distractor groups with squares and circles suggests that edge-based grouping exists (with squares), and that this is insensitive to the direction of brightness contrasts. Second, the contrast between performance with same and opposite polarity circles indicates a further mechanism sensitive to brightness contrast. This latter, brightness-based grouping may involve low spatial frequency sampling (blurring) of images, or token-based matching of image elements with the same contrast polarities (cf. Marr, 1982). Whichever the case, this last process seems qualitatively different and separable from the edge-based grouping process. Such evidence for two mechanisms of grouping in early vision is inconsistent with models that rely on a single early grouping process—be it low spatial frequency sampling alone (e.g.,

Watt, 1988) or on token-based matching (Marr, 1982). Our proposal for two early grouping mechanisms is consistent with the strong claim, made by Grossberg and colleagues, for the existence of separate brightness and edge-processing systems in vision (Grossberg & Mingolla, 1985; Grossberg & Todorovic, 1988). Grossberg and colleagues have argued for a brightness processing system (the FCS) that is functionally distinct from a system for edge processing (the BCS). The edge-based BCS supplies unsigned contours for brightness and hue-based filling in via the FCS. Our evidence, for grouping between opposite polarity elements providing collinearity is present, supports the notion of an edge-based grouping mechanism that is insensitive to the direction of brightness changes. However, we also found that there was only a relatively weak trend for an advantage when both edge- and brightness-based grouping could occur (with same polarity squares) relative to when only one form of grouping could occur (with same polarity circles and with opposite polarity squares, respectively). This result limits accounts of the relations between edge- and brightness-based grouping. For example, were either form of grouping completed first before the other gets underway (i.e., if the two grouping processes were serially ordered), then there should be an advantage for one grouping condition over the other.

Image blurring could account for the effects found for the grouping of the circle elements, based on a simple low spatial frequency signal, although such a process cannot account for the effect of collinear edges reported here or for other Gestalt grouping phenomena (Palmer, 1980). Using an approach based on that of Grossberg and colleagues, Neumann (1994) has proposed that prior to edge-based grouping taking place, there is a low spatial frequency blurring process in an earlier processing system (the so-called monocular preprocessing system). If this blurring was completed before input to the edge-based grouping mechanism taking place (e.g., in the BCS), we would expect an overall advantage for same polarity over opposite polarity stimuli (because grouping between same polarity elements would be completed before edge-based grouping between opposite polarity elements). We did not find this. In contrast, if edge- and brightness-based grouping operated independently and in parallel, with both providing separate inputs to an orientation-detection mechanism, we would expect a substantial advantage for stimuli that generate output from both mechanisms (e.g., same polarity squares) relative to the stimuli that generate output from only one (same polarity circles or opposite polarity squares). This follows from standard "horse race" models of information processing: Given overlap in the distribution of output times from two mechanisms, there will be a benefit for stimuli that generate responses as soon as one mechanism is completed without the delay present on trials when a single mechanism generates a slow response. Although we found a trend for an advantage, it was unreliable. A compromise account might be one in which the two grouping mechanisms are serially arranged, but with the output from one (e.g., an edge-based grouping process, insensitive to differences in contrast polarity) being made available to the second mechanism (im-

age blurring or token-based matching)³ before the first mechanism being completed. There may then be an advantage for performance when stimuli can be grouped by both mechanisms (e.g., same polarity squares), but it will be relatively weak when compared with either mechanism alone (as we observed).

As noted in the introduction, Elder and Zucker (1993) found that introducing elements with opposite contrast polarities disrupted grouping based on closure. Their finding contrasts with our null effect of the opposite contrast polarities when grouping was based on collinear edges. This contrast suggests that the mechanisms of grouping by collinearity and of grouping by closure may be functionally distinct because qualitatively different effects of a common variable are apparent. For example, within a framework such as that proposed by Grossberg and Mingolla (1985), it may be that collinearity is a property computed by the BCS and that closure is a property computed by the FCS and so grouping is sensitive to the direction of brightness change. Closure may be a property of surface rather than edge information in the images.

Whatever the case concerning closure, the present results demonstrate the existence of separate mechanisms for edge- and brightness-based grouping, that edge-based grouping is insensitive to the direction of brightness change, and that both edge- and brightness-based grouping operate in parallel across images. The findings are consistent with theories of parallel coding of complex image properties and with theories that distinguish between surface- and edge-based coding of images.

³ Note that RTs to contrast polarity squares tended to be faster than same polarity circles, suggesting that edge-based grouping is most usually completed first.

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