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Influence of inter-item symmetry in visual search

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Abstract—Does visual search involve a serial inspection of individual items (Feature Integration Theory) or are items grouped and segregated prior to their consideration as a possible target (Attentional Engagement Theory)? For search items defined by motion and shape there is strong support for prior grouping (Kingstone and Bischof, 1999). The present study tested for grouping based on inter-item shape symmetry. Results showed that target–distractor symmetry strongly influenced search whereas distractor–distractor symmetry influenced search more weakly. This indicates that static shapes are evaluated for similarity to one another prior to their explicit identification as 'target' or 'distractor'. Possible reasons for the unequal contributions of target–distractor and distractor–distractor relations are discussed.

Keywords: Visual search; visual attention; perceptual grouping; symmetry perception.

INTRODUCTION

Many visual events compete for our attention. How do we select one object (target) from among other objects (distractors)? According to Feature Integration Theory (Treisman, 1986; Treisman and Gelade, 1980) a target defined by a single feature (e.g. a red bike among blue bikes) will pop out from the distractors because single features are processed in parallel without attention. However, finding a target that is a conjunction of features (e.g. a small red bike among small blue bikes and large red bikes) will require a serial inspection of items, because attention is necessary to successfully conjoin their features.

But not all findings are as easily incorporated into Feature Integration Theory. For example, pop out search has been reported for a variety of feature conjunctions and complex spatial relations (Enns and Rensink, 1990; Nakayama and Silverman, 1986; McLeod *et al.*, 1988; Treisman, 1988). This has been accommodated by proposing that search may involve either the inhibition or excitation of all items

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sharing one of the target features (Treisman and Sato, 1990; Wolfe *et al.*, 1989; Wolfe, 1994). That is, to find the small red bike among small blue and large red bikes, one might inhibit all the large bikes, causing the small red bikes to pop out from among the small blue bikes.

Duncan (1995) noted that while such a solution was theoretically plausible, serial models could not accommodate findings that demonstrated the importance of *perceptual grouping* of items in a search display. This point was driven home by a detailed consideration of a study by Driver *et al.* (1992), who found that a common direction of motion among target and distractor items in the search display allowed search to proceed more efficiently than when items in the display moved out of phase with one another. Because motion phase is, by definition, concerned with the interaction of items in the display to one another, serial search theories that emphasize attentional allocation on an item-by-item basis do not fit these results.

On the other hand, a theory of visual search that emphasizes *interactions* among items within a display is uniquely poised to explain the effects of motion phase on visual search performance. This is precisely the emphasis adopted by Duncan and Humphreys' (1989, 1992) Attentional Engagement Theory. According to this theory, perceptual grouping is critical to understanding visual search in general, and grouping by motion is crucial in particular for understanding the Driver *et al.* (1992) results.

Kingstone and Bischof (1998) undertook an explicit test of this hypothesis. In addition to replicating the Driver *et al.* results, they also moved a random set of dots in phase or counter phase to the target and distractor motion directions. They demonstrated that item grouping based on motion direction had a dramatic effect on search, and as such strongly supported Attentional Engagement Theory (see also Watson and Humphreys, 1999).

Yet Attentional Engagement Theory proposes that search speed and accuracy depend on grouping of search items even when none of the items are in motion. The present study put this idea to a direct test using the relatively complex grouping property of inter-item symmetry. To see why this grouping property was the focus of the present study, it is helpful to review briefly how grouping (also called perceptual organization) has been examined in previous studies.

Visual search and grouping of static items

The earliest reports of gestalt grouping effects on visual search reported that discrimination of two target letters (T *vs.* F) was influenced by the spatial configuration of other non-target elements in the display (Banks and Prinzmetal, 1976; Prinzmetal and Banks, 1977). When the target was an element in a larger configuration defined by good continuation or closure, its discrimination was slower and less accurate than when the target was an element that stood apart from these configurations. In related work, Treisman (1982) showed that when search items were clustered by proximity, such that a unique feature of color or orientation defined the target within the cluster, search time depended on the number of clusters, not the total number of items in the display. This suggested that these homogeneous distractors were organized into spatial groups prior to attention being focused on the target.

Later studies explored the influence of other grouping principles, including connectivity (Trick and Enns, 1997), spatial separation among elements (Olds *et al.*, 1999), contrast polarity (Enns and Kingstone, 1995), and color (Kaptein *et al.*, 1995). However, in each case the factors that were studied involved the grouping of a relatively homogeneous set of distractors on the basis of a simple visual property such as proximity, closure, connectivity or color. This meant that search could be limited to a restricted subset of the items either through the parallel grouping processes proposed by Attentional Engagement Theory (Duncan and Humphreys, 1989, 1992) or through the inhibition or excitation of all items sharing a particular simple feature as proposed by Feature Integration Theory (Treisman and Sato, 1990) and Guided Search Theory (Wolfe *et al.*, 1989; Wolfe, 1994).

Scope of the present study

In the present study we tested whether grouping based on inter-item symmetry would occur in a search task involving static displays and a target defined by a specific shape. We selected the complex visual property of inter-item symmetry as the potential grouping factor for two reasons. First, precisely because inter-item symmetry cannot be defined by any simple geometric property (e.g. orientation, curvature) or intensive property (e.g. luminance, color), it is an ideal candidate for testing the grouping of static items. If evidence for grouping can be found for this property it would stretch the limits of credulity to claim it was accomplished by the inhibition of individual items sharing a topographic map for a simple visual property (Treisman and Sato, 1990; Wolfe, 1994).

Second, inter-item symmetry is based on a well-established anisotropy: Shapes that are identical when reflected across the vertical axis (e.g. p *vs.* q) are perceived as more similar than shapes that are identical when reflected across the horizontal axis (e.g. p *vs.* b) (Cairns and Steward, 1970; Hershenson and Ryder, 1982; Bagnara *et al.*, 1983). This means that all geometric differences between shapes can be controlled between the condition in which stronger grouping is predicted to occur (vertical symmetry) and the condition in which weaker grouping is predicted (horizontal symmetry). Any differences in search speed or accuracy must be attributed to the tendency for items to vary in similarity as a function of their axis of symmetry.

It is important to note that our interest in inter-item symmetry is distinct from the question of whether search is influenced by the internal symmetry of search items. It is generally acknowledged that patterns that are internally symmetric are detected more rapidly and accurately than patterns that are not internally symmetric (Corballis and Roldan, 1974; Palmer and Hemenway, 1978). Previous studies of symmetry in visual search have tended to use items containing internal symmetry, even in studies aimed at examining the role of inter-item symmetry (e.g. Davis *et al.*, 2003; Wagemans, 1993, 1995; Wolfe and Friedman-Hill, 1992). This means that they have not tested solely for influences of inter-shape symmetry. It also means they have not tested separately for influences stemming from target–distractor *vs*. distractor–distractor symmetry. This is because internally asymmetric items are needed to create sets of three or more display items, in which two are distractors that are symmetric with one another and one is a target that is distinct in some way from these two distractors.

We tested for grouping of static shapes in Experiment 1 by varying the symmetry between the target and homogeneous distractor items that were themselves not internally symmetric (p–q and p–b). If the target shape (p) was found less readily among vertically symmetric distractors (q) than among horizontally symmetric distractors (b) it would mean that symmetry was being evaluated during search. However, target–distractor symmetry effects are consistent with both a serial inspection of items and a parallel evaluation of items. A critical test of the grouping hypothesis derived from Attentional Engagement Theory is that items in the search display would group with one another prior to the identification of the target shape.

In Experiments 2–4 we varied the symmetry among heterogeneous distractor items to test that prediction; distractors were multiple copies of two shapes that were symmetrical with one another either over the vertical or the horizontal axis. In pilot tests we first asked participants to search for target shapes that were quite distinct from either of these two distractors and that did not share any symmetry relations with them (e.g. an 8 target among p and q distractors). Search was so efficient under these conditions that search time and accuracy were constant over display size. Thus a more difficult search task was required to measure the predicted effects of differential grouping for the two distractor conditions (symmetry over the vertical *vs*. horizontal axis).

This goal was achieved by requiring participants to search for target shapes that were very similar to one of the two distractor shapes. These targets differed from this distractor in that they had a distinctive feature that was added to the larger shape (e.g. a gap or a hash mark). Importantly, these added features did not alter the overall shapes of the items. This meant that if grouping occurred among the distractors based on their shape symmetry with one another, it would make it more *difficult* to find the target than if grouping did not occur. Specifically, grouping of the distractors meant that search for the distinctive feature could not be restricted as easily to the smaller subset of items sharing the target shape.

It is important to note that this design leads to predictions for the influence of distractor–distractor similarity that are superficially opposite from those usually associated with Attentional Engagement Theory. Normally, when there are three shapes (one target and two distractors) increased distractor–distractor similarity *improves* search because any grouping among the distractors will help segregate them from the target shape (Kingstone and Bischof, 1999). However, when there are only two shapes, as in the present design (the target shares its shape with one distractor, the other distractor differs) increased distractor–distractor similarity is predicted to impair search because grouping of the distractors will mean that search for the target shape cannot be restricted as easily to a subset of the display items. Instead, the target shape will now be camouflaged among the high-similarity distractor shapes.

EXPERIMENT 1A: TARGET–DISTRACTOR SYMMETRY

Experiment 1A tested whether the symmetry relations between targets and distractors influenced visual search. Targets were symmetrical to distractors over either the vertical or horizontal axis.

Method

Participants. Twelve participants (4 male and 8 female) aged 18 to 28 from the University of British Columbia undergraduate subject pool participated. Eleven were right handed; one was left-handed. All reported normal or corrected-to-normal vision.

Stimuli. Search displays were presented on an iMac computer, with 800 × 600 screen resolution (95 Hz), using VScope software (Enns and Rensink, 1991). The target (a lower-case letter p) was symmetrical to distractors over either a vertical axis (a lower-case letter q) or a horizontal axis (a lower-case letter b). All stimuli subtended a visual angle of 0.8 × 0.5 degrees. Figure 1A illustrates the design of the search items and Fig. 2A shows a sample search display.

Procedure. Participants indicated the target was present by pressing the '/' key and that it was absent by pressing the 'z' key. The display remained on the screen until the response. After a response, feedback was given for 0.5 s, in the form of a plus sign (+) if the response was correct, and a minus sign (−) if the response was incorrect. This symbol became the fixation point for the next search display.

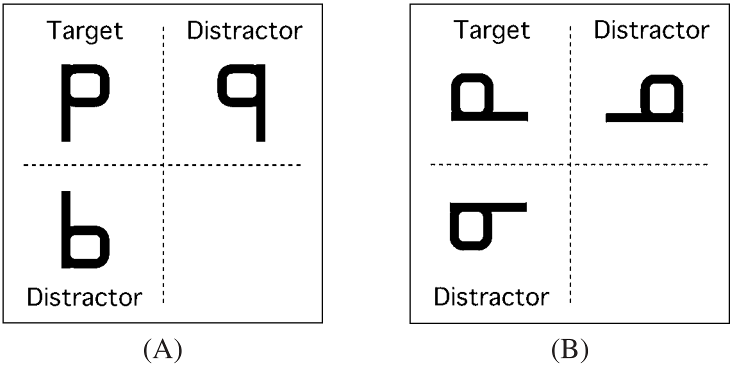

Figure 1. Visual search stimuli in Experiment 1. (A) Familiar orientation. (B) Unfamiliar orientation.

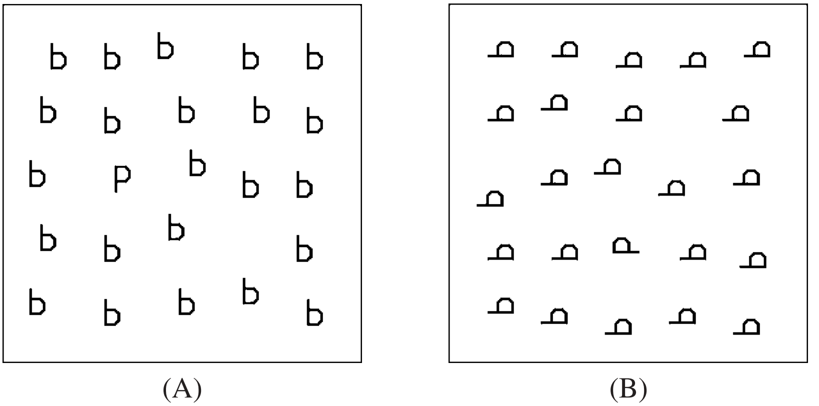

Figure 2. Example visual search displays in Experiment 1. (A) Familiar orientation. (B) Unfamiliar orientation.

Display size was varied randomly between 8, 16, and 24 elements. Each participant performed a total of 10 blocks of 60 trials.

Results

Mean correct response time (RT) and mean proportion errors are shown in Fig. 3. These data show that search was strongly influenced by the axis of symmetry between target and distractor items. When the target was symmetrical with distractors over the vertical axis, search was generally slower (by more than 200 ms) and less accurate (by more than 10%) than when the symmetry was over the horizontal axis. However, there were no differences in search rate associated with axis of symmetry, with display size having very similar effects in the two symmetry conditions (Vertical: mean RT slope = 14 ms per item, mean error slope = 0.71% per item; Horizontal: mean RT slope = 12 ms per item, mean error slope = 0.47% per item).

These conclusions were supported by a $2 \times 2 \times 3$ analysis of variance (ANOVA) for both RT and errors, involving the factors of Symmetry (vertical, horizontal), Display Size (8, 16, and 24 items), and Target (present, absent). These analyses revealed a significant main effect of Symmetry [RT: $F(1, 11) = 42.61$, $p < 0.01$; errors: $F(1, 11) = 29.601$, $p < 0.01$], indicating generally faster and more accurate search for horizontal than for vertical symmetry. A main effect of Display Size [RT: $F(2, 11) = 98.5$, $p < 0.01$; errors: $F(2, 11) = 9.94$, $p < 0.01$] reflected the expected increase in search time and errors with increases in the number of distractors. A main effect of Target was observed only for RT [$F(1, 11) = 19.72$, $p < 0.01$], reflected generally slower search on target absent than target present trials.

There was also a significant interaction of Symmetry × Target [RT: $F(1, 11) = 11.49$, $p < 0.01$; errors: $F(1, 11) = 6.573$, $p < 0.05$], with larger symmetry effects on target present than on target absent trials. Another interaction involved

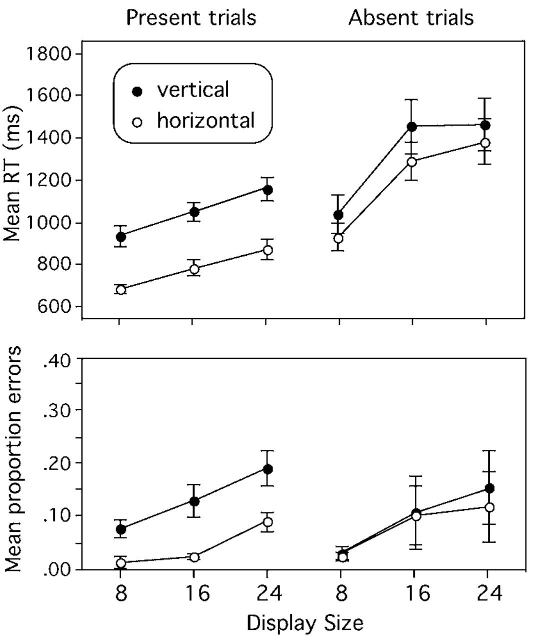

Figure 3. Mean correct RT and mean proportion errors in Experiment 1A.

Display Size × Target for RT [$F(1, 11) = 31.74$, $p < 0.01$], with generally steeper RT slopes as a function of display size for target absent trials (28 ms per item) than for target present trials (13 ms per item). No other effects were significant. The most notable among these non-significant interactions was Symmetry × Display Size [both RT and errors: $F(2, 11) < 1$]. Thus, although item symmetry had a strong effect on overall search speed and errors in this experiment, it did not influence the rate at which participants were able to search.

EXPERIMENT 1B: TARGET–DISTRACTOR SYMMETRY IN UNFAMILIAR SHAPES

Experiment 1B was conducted with the same participants as in Experiment 1A, with the testing sessions counterbalanced in order to control for order effects. The critical difference between experiments was the orientation in which the items (p, q, and b) were presented. Previous research using letter stimuli (Wang *et al.*, 1994) suggests that there may have been no RT slope differences in Experiment 1A because the target item was a highly familiar letter (p). By rotating all the items by 90 degrees in the present experiment, the geometrical factors would remain constant while the familiarity of the search items would be reduced.

Results

Mean correct response time (RT) and mean proportion errors are shown in Fig. 4. As in Experiment 1A, search in the horizontal symmetry condition was faster and more accurate than in the vertical symmetry condition. However, unlike Experiment 1A, there were now also search rate differences that could be attributed to item symmetry. Whereas search in the horizontal condition was conducted at 7 ms per item (0.04% increase in errors per item) when the target was present, search took 16 ms per item (1.44% increase in errors per item) in the vertical condition.

ANOVA supported this conclusion by showing significant interactions of Display Size and Symmetry. The three-way interaction of Symmetry × Display Size × Target was significant for errors [$F(2, 22) = 6.77$, $p < 0.01$], although not for RT [$F(2, 22) = 2.38$, $p > 0.10$]. This reflected the significantly steeper error slopes for target present trials in the vertical condition than in the horizontal condition. In addition, the two-way interaction of Symmetry × Display Size was significant for errors [$F(2, 22) = 10.75$, $p < 0.01$], indicating that the slope difference between the symmetry conditions was significant even when target present and absent trials were combined.

All three main effects were also significant. Symmetry [RT: $F(1, 11) = 59.05$, $p < 0.01$; errors: $F(1, 11) = 51.74$, $p < 0.01$], indicated generally more efficient search for horizontal than for vertical symmetry. Display Size [RT: $F(2, 22) = 57.05$, $p < 0.01$; errors: $F(2, 22) = 17.00$, $p < 0.01$] reflected

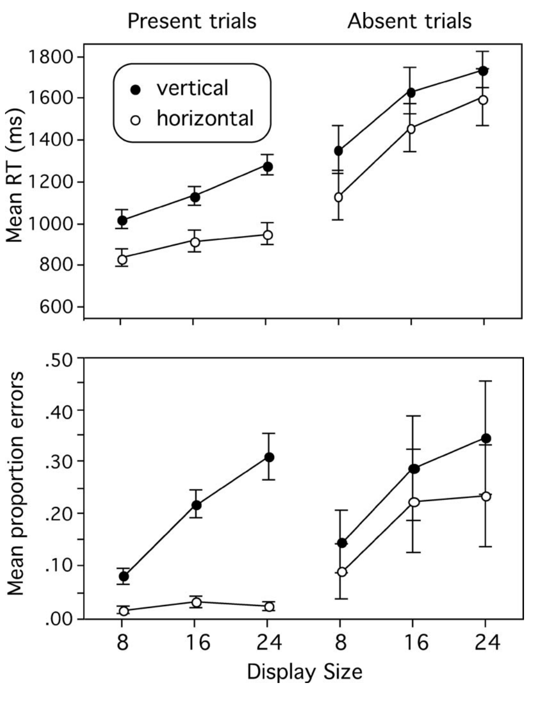

Figure 4. Mean correct RT and mean proportion errors in Experiment 1B.

the expected increases in search time and errors with increases in the number of distractors. Target was significant only for RT [$F(1, 11) = 38.23$, $p < 0.01$], reflecting generally slower search on target absent than target present trials.

As in Experiment 1A, other significant interactions concerned Symmetry × Target [errors: $F(1, 11) = 5.76$, $p < 0.01$], with larger symmetry effects evident on target present trials than on target absent trials. Another interaction in RT involved Display Size × Target [$F(2, 22) = 18.27$, $p < 0.01$], with generally steeper RT slopes for target absent trials (27 ms per item) than for target present trials (12 ms per item). No other effects were significant. Taken together, these results show that target-distractor symmetry relations can have an influence on overall search time and search rate when the items are shapes in unfamiliar orientations.

EXPERIMENT 2: DISTRACTOR–DISTRACTOR SYMMETRY RELATIONS

The results of Experiment 1 make it clear that the axis of symmetry between targets and distractors influences overall search time and search rate, especially when the shapes in the search task are in an unfamiliar orientation. In Experiment 2 we began to examine the influence of symmetry on distractor–distractor relations.

To do this we needed to have at least two kinds of distractors that could be related to one another by symmetry. Items such as those used in Experiment 1 met these requirements, but it was not immediately clear what the target item should then be. Our pilot work indicated that if the target differed from the distractors in overall shape, then search times were influenced by target–distractor similarity over and above any of the distractor–distractor effects we wished to study. To isolate the effects for distractor grouping, we arrived at a solution in which the target was identical in overall shape to one of the distractor items in each of the symmetry conditions. In this design, increased distractor–distractor similarity is predicted to *impair* search because grouping among the distractors will mean that search for the target shape cannot be restricted as easily to a subset of the display items.

The specific items used in Experiment 2 are shown in Fig. 5. Searching for this target among these distractors meant that any target–distractor grouping effects would be equated across symmetry conditions. This was because the target was

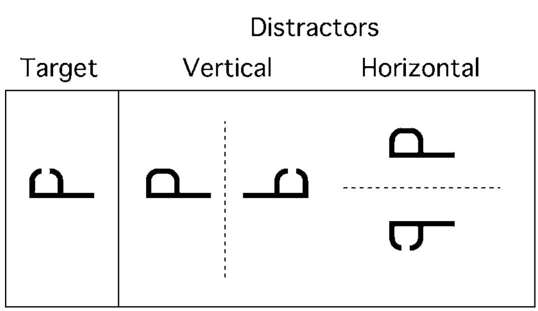

Figure 5. Visual search stimuli in Experiment 2.

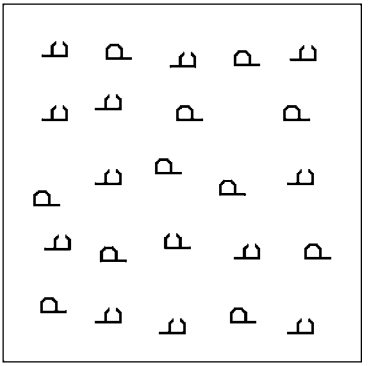

Figure 6. Example visual search display in Experiment 2.

distinguished from these distractors, not by its overall shape, nor by the presence of a distinctive feature (the gap), but by the conjunction of shape and distinctive feature. If symmetry grouping occurred among these sets of distractors it would be more difficult to find the target among the distractors that were vertically symmetric, since their grouping would make it more difficult to restrict attention to the subset of shapes that included the target. A sample search display is shown in Fig. 6.

Method

Methods were identical to Experiment 1 with the following exceptions. Twelve participants (2 male and 10 female), aged 18 to 29, participated. Eleven were right handed. The target was a rotated p with a small gap in the rounded segment. One half of the distractors in each symmetry condition were rotated p's without gaps. In the vertical condition the other one half of the distractors were rotated b's with gaps; in the horizontal condition the other one half of the distractors were rotated q's with gaps.

Results

Mean correct RT and mean proportion errors are shown in Fig. 7. The results showed first of all that this search task was considerably more difficult than the task in Experiment 1. Instead of search slopes in the teens, search time was now increasing by more than 100 ms with each additional display item. Second, the results showed that the axis of symmetry had an influence on overall search speed. When distractors were symmetrical over the vertical axis, search was generally slower (by more than 400 ms) and less accurate (by more than 5%) than when they were symmetrical over the horizontal axis. Third, there were symmetry-related differences in search rate, with the vertical condition averaging an increase in RT of 153 ms per item (0.42% increase in errors per item) and the horizontal condition averaging an increase in RT of 131 ms per item (0.22% increase in errors per item).

ANOVA indicated that the two-way interaction of Symmetry × Display Size was significant for both measures [RT: $F(2, 22) = 15.48$, $p < 0.01$; errors:

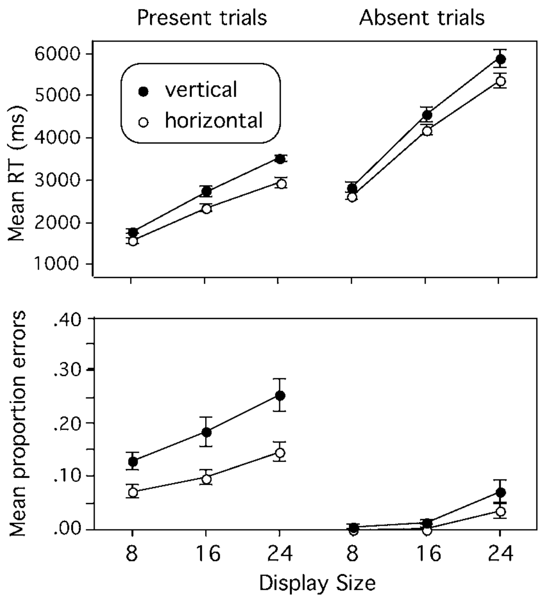

Figure 7. Mean correct RT and mean proportion errors in Experiment 2.

$F(2, 22) = 30.4$, $p < 0.01$], reflecting significantly less efficient search rates for vertical than for horizontal symmetry.

All main effects were also significant. Symmetry [RT: $F(1, 11) = 169.79$, $p < 0.01$; errors: $F(1, 11) = 36.93$, $p < 0.01$], indicated generally better search for horizontal than for vertical symmetry. Display Size [RT: $F(22, 2) = 542.6$, $p < 0.01$; errors: $F(22, 2) = 38.69$, $p < 0.01$], reflected the expected increase in search time and errors with increases in display size. Target [RT: $F(1, 11) = 468.95$, $p < 0.01$; errors: $F(1, 11) = 39.69$, $p < 0.01$], reflected generally slower and less accurate search on target absent than target present trials.

Display Size × Target was significant for RT [$F(2, 22) = 103.84$, $p < 0.01$], with generally steeper RT slopes for target absent trials (185 ms per item) than for target present trials (99 ms per item). It was also significant for errors [$F(2, 22) = 3.46$, $p < 0.05$], although in this measure the increase in errors was greater for target present trials (0.63% increase in errors per item) than target absent trials (0.32% increase per item). No other effects were significant.

These results show that symmetry relations among distractors can influence visual search, just as do symmetry relations among targets and distractors. However, the results of Experiment 2 are very difficult to compare with the results of Experiment 1, because of the large baseline differences in the difficulty of the search. This makes it impossible to compare whether the magnitude of the symmetry effects for distractors is comparable to those for targets and distractors. The aim of the next experiment was to test for distractor symmetry effects in an experiment in which the overall difficulty of the search was more similar to Experiment 1.

EXPERIMENT 3: NO DISTRACTOR SYMMETRY EFFECTS IN EASIER SEARCH

The search items used in Experiment 3 are shown in Fig. 8. The design of these stimuli was identical to those in Experiment 2, with two exceptions. First, the distinctive feature contained in the target shape involved the location of a positive feature (i.e. the small central hash mark) rather than the deletion of a feature (i.e. the gap). Considerable evidence in the visual search literature shows that search for the presence of a feature is more efficient than search for its absence (Treisman, 1988). Second, the overall shape was a rotated L shape rather than a P, since two Ls that differed only in their mirror image symmetry appeared in pilot tests to be more dissimilar than two Ps.

Method

Methods were identical to Experiment 1 with the following exceptions. Sixteen students (2 male and 14 female), aged 19 to 40 participated. All were right handed. The target was a rotated L shape with an ascending hash mark. One of the distractors in each condition was similar in shape with the exception that the center mark was descending. The other distractor was then either mirror imaged over the vertical over the horizontal axis.

Results

Mean correct RT and mean proportion errors are shown in Fig. 9. There were two main results. First, the overall difficulty of the search task was now very similar to that in Experiment 1: the search rate on target present trials was 16 ms per item on average and the corresponding increase in errors was 0.002% per item. Second, there was no evidence at all that distractor symmetry had any influence on search.

ANOVA showed significant main effects of Display Size [RT: $F(1, 15) = 64.60$, $p < 0.01$, errors: $F(1, 15) = 25.50$, $p < 0.01$], and Target [RT: $F(1, 15) = 89.47$, $p < 0.01$; errors: $F(1, 15) = 13.49$, $p < 0.01$], but not of Symmetry or Symmetry $\times$ Display Size [all $F_s < 1.0$].

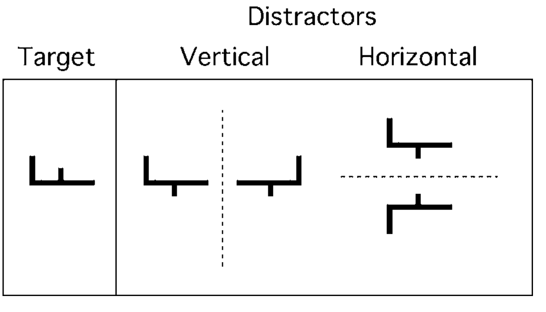

Figure 8. Visual search stimuli in Experiment 3.

Display Size × Target was significant for both measures [RT: $F(2, 30) = 47.59$, $p < 0.01$; errors: $F(2, 30) = 9.63$, $p < 0.01$], reflecting the generally slower search rate on target absent trials (51 ms per item) than on target present trials (16 ms per item); and a greater increase in errors for target present (0.002% reduction per item) than target absent trials (0.0002% reduction per item). No other effects were significant.

These results suggest that when search is comparable in difficulty to Experiment 1, where target–distractor effects were observed, distractor symmetry effects were not observed. Yet, Experiment 2 revealed distractor symmetry effects when the task was much more difficult. This suggests that distractor symmetry effects are weaker overall than target symmetry effects.

However, there is one more issue that deserves to be explored before this conclusion is accepted. The literature on symmetry perception shows that sensitivity to symmetry decreases as the symmetrical parts of the pattern are viewed further away from the fovea (Gurnsey *et al.*, 1998). This suggests that distractor symmetry effects may also be subject to this limitation of visual eccentricity, since on average most of the distractors are being viewed away from fixation at any given moment. If so, then distractor symmetry effects should be enhanced if the distractors are appropriately scaled in size so that they are all equally visible when the eye is on the fixation point (Sally and Gurnsey, 2001). Cortical scaling or magnification of this kind has previously proven effective in eliminating issues of retinal eccentricity in visual search (Carrasco and Frieder, 1997; Carrasco *et al.*, 1995).

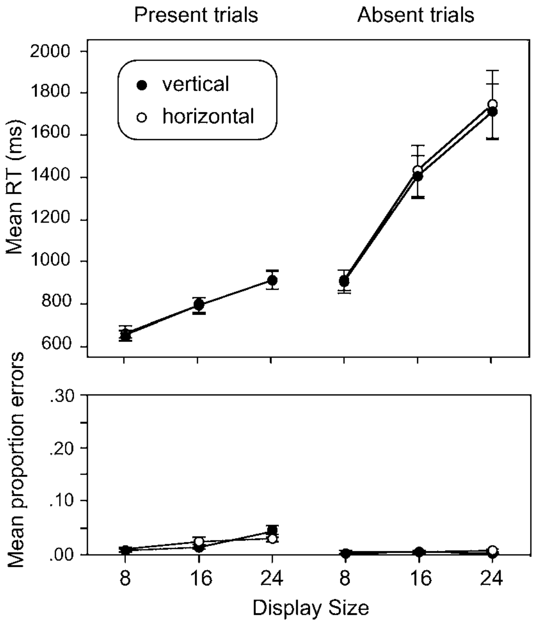

Figure 9. Mean correct RT and mean proportion errors in Experiment 3.

EXPERIMENT 4: CORTICAL MAGNIFICATION REINSTATES DISTRACTOR SYMMETRY EFFECT

An example of the search displays used in Experiment 4 is shown in Fig. 10. The design of this experiment was identical to the previous one with the exception that the search items were scaled in a linear fashion as a function of their distance from the center of the display.

Method

Thirty-six participants were tested (24 female, 31 right handed, aged 18 to 27). The search items were presented in three different sizes (0.6×0.8 degrees, 1.5×1.9 degrees, and 3.7×3.9 degrees) at three different distances from the display center (1.3, 2.8, and 6.0 degrees). Participants were instructed to fixate on a central fixation cross throughout each search trial, which appeared alone for 240 ms before the search display appeared. The location of distractors was varied randomly among the three different distances from fixation in each display. Display sizes tested were 6, 12, and 18, with an equal number of items at each eccentricity in each display.

Results

Mean correct RT and mean proportion errors are shown in Fig. 11. The results showed first that this search task was comparable in overall difficulty to Experiments 1 and 3 and not as difficult as Experiment 2. Average RT slopes were now 40–50 ms per item for target present trials and 70–90 ms per item for target absent trials. Second, there were symmetry-related differences in search rate, with target present trials in the vertical condition averaging an increase in RT of 54 ms per item (1.42% increase in errors per item) and the horizontal condition averaging an increase in RT of 44 ms per item (0.92% increase in errors per item).

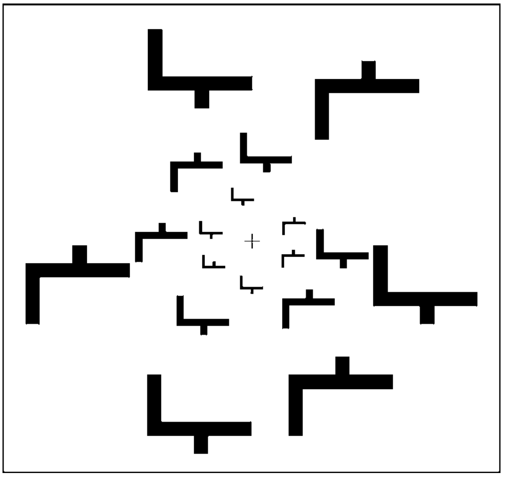

Figure 10. Example visual search display in Experiment 4.

ANOVA indicated that interactions involving Symmetry were significant for both measures: Symmetry × Display Size × Target [RT: $F(2, 70) = 3.47$, $p < 0.04$, errors: $F(2, 70) = 1.61$], Symmetry × Display Size [RT: $F(2, 70) = 4.15$, $p < 0.02$, errors: $F(2, 70) = 3.44$, $p < 0.05$] and Symmetry × Target [RT: $F(1, 35) = 5.76$, $p < 0.03$]. These effects reflected significantly slower and less accurate search rates for vertical than for horizontal symmetry.

All main effects were also significant. Symmetry [RT: $F(1, 35) = 29.95$, $p < 0.01$; errors: $F(1, 35) = 3.92$, $p < 0.05$], indicated generally better search for horizontal than for vertical symmetry. Display Size [RT: $F(2, 70) = 233.78$, $p < 0.01$; errors: $F(2, 70) = 54.53$, $p < 0.01$], reflected the expected increase in search time and errors with increases in display size. Target [RT: $F(1, 35) = 106.71$, $p < 0.01$; errors: $F(1, 35) = 192.27$, $p < 0.01$], reflected generally slower and less accurate search for target absent than target present trials. Size [RT: $F(2, 70) = 48.95$, $p < 0.01$; errors: $F(1, 35) = 12.27$, $p < 0.01$] reflected generally faster and more accurate search for the medium size targets than for either large or small targets.

Display Size × Target was significant for RT [$F(2, 70) = 69.84$, $p < 0.01$], with generally steeper RT slopes for target absent trials than target present trials. It was also significant for errors [$F(2, 70) = 54.64$, $p < 0.01$], although in this measure the increase in errors with display size was greater for target present trials than target absent trials.

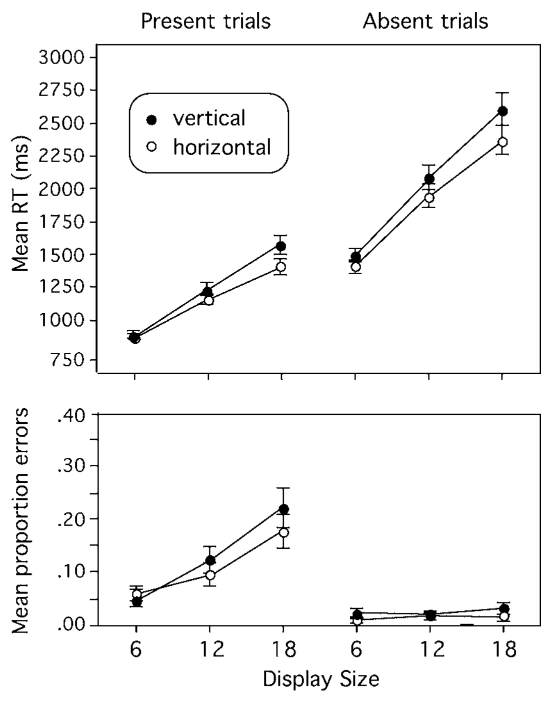

Figure 11. Mean correct RT and mean proportion errors in Experiment 4.

The only other significant effects all involved the factor of Size, with the medium size letters generally have shorter search times and faster search rates [RT: Size $\times$ Target $\times$ Display Size, $F(4, 140) = 7.38$, $p < 0.01$; Size $\times$ Display Size, $F(4, 140) = 13.93$, $p < 0.01$; Size $\times$ Target, $F(2, 70) = 51.00$, $p < 0.01$; errors: Size $\times$ Target $\times$ Display Size, $F(4, 140) = 10.76$, $p < 0.01$; Size $\times$ Display Size, $F(4, 140) = 8.14$, $p < 0.01$; Size $\times$ Target, $F(2, 70) = 3.44$, $p < 0.04$]. These results therefore show that symmetry relations among distractors influence visual search when the search displays have been cortically magnified.

GENERAL DISCUSSION

Attentional Engagement Theory (Duncan and Humphreys, 1989, 1992) predicts that visual search through displays of static items will be influenced by both target–distractor and distractor–distractor similarity. These similarity relations are further proposed to result in perceptual grouping of the items in the display. Such grouping will mean that search difficulty will generally increase as a function of the target–distractor similarity and that it will generally decrease as a function of distractor–distractor similarity. In this section we will first describe our results and their implications with regard to Attentional Engagement Theory. Then we will consider some alternative explanations of the results and make suggestions for future work to answer some unresolved questions.

The present study tested these ideas by having participants search for shapes that shared symmetry with another. This complex visual property was selected as the potential grouping factor because inter-item symmetry cannot be defined by any simple geometric or intensive visual property, making it unlikely that search could be influenced by the selective inhibition of individual items sharing a property of one of the topographic maps in the visual cortex (Treisman and Sato, 1990; Wolfe, 1994).

The goal of testing target–distractor relations was easily accomplished by having the target of the search share either vertical symmetry (high similarity) or horizontal symmetry (low similarity) with the distractors in the displays. This relation has been tested in previous studies (Davis *et al.*, 2003; Wolfe and Friedman-Hill, 1992) and these have pointed to the same result: search is slower and less accurate when a target is vertically symmetric with the distractors. However, previous studies have used items that are internally symmetrical as well. As such, they have only examined target–distractor symmetry by varying item orientation (e.g. \ *vs.* /); they have not tested items that are internally asymmetric, nor have they tested items that have the same principle orientation (e.g. p *vs.* q).

This was tested in the present Experiments 1A and 1B and the results showed clearly that target–distractor symmetry influenced search. Search was generally slower and less accurate for targets that shared vertical symmetry with the distractors than when the same targets shared only horizontal symmetry with the distractors (Experiment 1A). When the items were placed into an unfamiliar orientation (e.g.

rotated p *vs*. rotated q) this result was again obtained (Experiment 1B). In addition, when items were in an unfamiliar orientation, search for targets that shared vertical symmetry with the distractors resulted in larger increases in errors with display size.

The goal of testing distractor–distractor symmetry relations in search required a somewhat more complex design. First, because at least two different distractor items were required, the shape could not be internally symmetric (the mirror image of an internally symmetric shape is identical). Second, it was important to test distractor–distractor symmetry without confounding that relationship with symmetry relations that might exist between the target and the distractors. This meant that the target should not differ in its symmetry relations with the distractors, but should instead be defined by the possession of a unique feature. Third, the unique feature should not be one that itself permits grouping (e.g. color) since that might confound the measurement of any grouping effects due to symmetry. These three considerations led to the stimulus sets shown in Figs 5 and 8, where distractor sets were first drawn that contained the required symmetry relations and then targets were defined by the conjunction of one of the distractor shapes along with a distinctive feature (e.g. gap or hash mask location). Importantly, in this design, increased distractor–distractor similarity was predicted to impair search because grouping among the distractors means that search for the target shape cannot be restricted as easily to a subset of the display items.

Experiment 2 tested this design and found evidence of distractor–distractor grouping on the basis of inter-item symmetry. It was more difficult to find the target shape among distractors that shared vertical symmetry with one another than among the same distractors when they shared horizontal symmetry. However, this search task was also considerably more difficult overall than search had been in Experiment 1. In an effort to be able to compare distractor–distractor symmetry effects more directly with the target–distractor effects in Experiment 1, a more discriminable set of stimuli was tested in Experiment 3. Although this met the goal of testing for these effects in the context of a much easier search task, the results failed to reveal any influences of distractor–distractor symmetry. Finally, in Experiment 4, we repeated the design of Experiment 3 with search displays that were cortically magnified (i.e. items increased in size with eccentricity) in an effort to equate the visibility of all items in the display. This time distractor–distractor symmetry had an influence on search such that targets were most difficult to find among distractors that were symmetrical with one another about the vertical axis.

We interpret Experiments 2 and 4 as showing that distractors in static search displays are, at least under some conditions, perceptually grouped on the basis of inter-item symmetry. Taken together with Experiment 3, where the overall search performance and type of display (all items equal in size) were most similar to Experiment 1 and yet distractor symmetry had no influence on search, these findings suggest that that the influence of distractor–distractor symmetry is not as strong as that of target–distractor symmetry. There are several possible implications of this finding. Here we simply point to two of them; a definitive understanding of this relative difference in influence will have to await further research.

One reason for the stronger influence of target–distractor symmetry is suggested directly by an aspect of Attentional Engagement Theory that has not yet been systematically explored in the visual search literature. This concerns the double role played by the 'target template' in the determination of search efficiency. Attentional Engagement Theory holds that search is accomplished by a parallel-stage comparison between the target template and all items in the visual display (Duncan and Humphreys, 1989, 1992). Through a series of recursive parallel steps, weights are assigned to all the items in a display on the basis of their similarity to the search image and to one another. This means that the more similar a distractor is to the target, the larger will be the number of recursive steps that are needed to differentiate the target in the display from the distractors. Distractors will also tend to be grouped to one another through the spreading activation that occurs for similar items in a display.

The finding of a stronger influence of target–distractor symmetry in the present study could mean therefore that symmetry is evaluated twice — once in the parallel stage of processing just described and once again when the winning item from that competition is placed into the serial stage of short term visual memory in order to respond in the task. If symmetry does play a role in both of these stages it could explain why target–distractor symmetry is stronger, since it could have an influence both at the early parallel stage of grouping and in the later serial stage of decision-making and response. Distractor–distractor symmetry, on the other hand, could only play a role in the early parallel stage.

A second possibility is that the similarity metric underlying target–distractor and distractor–distractor relations is not exactly the same. For example, perhaps the criteria used for evaluating the similarity of all items to the target template is different from the criteria used to form linkages among the items in the display. One ecologically motivated reason for suspecting that 'similarity' might be evaluated differently in these two aspects is because it could be detrimental if objects throughout our visual field were strongly bound in an automatic fashion. Instead, perhaps the spreading evaluation of similarity is dampened as a function of eccentricity. This would serve to maintain greater flexibility of perception as new objects are brought to the fovea and reduce the computational demands of perception. It would also explain why distractor–distractor effects were so difficult to find until the displays were cortically magnified. In any case, it will be important in future work to study more systematically the bases used for determining similarity in these two computationally distinct aspects of Attentional Engagement Theory.

Alternative accounts and future directions

Although the motivation for this study and interpretation of its findings was provided by Attentional Engagement Theory, it is worth considering the findings in light of Feature Integration Theory (Treisman, 1986; Treisman and Gelade, 1980) and subsequent efforts to account for grouping within a model of search that is fundamentally serial, with subset selection occurring through the parallel inhibition or excitation of items sharing a display feature (Treisman and Sato, 1990; Wolfe, 1994; Wolfe *et al.*, 1989). Such a comparison should help highlight unresolved issues and point to directions for future research that might clarify these issues.

As mentioned in the Introduction, the findings of target–distractor symmetry effects in Experiment 1 are consistent with both a serial and a parallel evaluation of items. Thus, these results and similar results of Davis *et al.* (2003) and Wolfe and Friedman-Hill (1992), do not pose any interpretational problems for serial search models. What is more difficult to explain with a serial model is the effect of distractor–distractor symmetry in Experiments 2 and 4. One way to salvage a serial interpretation here might be to argue that search was accomplished in Experiment 2 (see Fig. 6) by the prior selection of only those items containing a distinctive gap (either through excitation of all gap items or inhibition of all non-gap items). Such prior selection would leave the task as involving search for a target among distractor shapes that shared either vertical or horizontal symmetry. The results in Experiment 2 would then be merely a replication of the finding in Experiment 1 that target–distractor symmetry influences search.

Two observations argue against this interpretation. First, distractor–distractor symmetry effects were more difficult to obtain than target–distractor symmetry effects. They were only observed in a much more difficult search task (Experiment 2) or when search items were cortically magnified (Experiment 4). They were not observed in Experiment 3, which was in its important respects a replication of the concepts illustrated in Experiment 1. This imbalance in the findings means, at a minimum, that some other factor is involved than the mechanisms proposed by serial search models.

Second, the candidate feature for prior selection in Experiments 3 and 4 is not easy to identify (Fig. 8). It cannot be the relative location of the hash mark, since the mark descends from all shapes in the vertical symmetry condition and it alternately ascends and descends from the shapes in the horizontal symmetry condition. Incidentally, if the relative location of the mark could be used to guide search, the fact that it descends from both distractors while it ascends for the target shape, should have made search in the vertical condition easier than in the horizontal condition. The results in Experiment 4 were the opposite. Finally, note that the feature of proposed prior selection for the serial models cannot be the overall shape of the item (e.g. an L oriented in one direction or the other). Having such a high-order relational feature as the basis of selection violates the spirit of having parallel inhibition or excitation operate from topographically organized feature maps in the brain. Nothing like this has been claimed for the serial models. The stimulus set of Experiments 3 and 4 clearly leave little for a prior selection mechanism to work with. Nonetheless, there may still be a way for serial models to accommodate these interactive effects of heterogeneous distractors on search. In that case the present results provide important demonstrations of the range of findings that must be explained through modifications to the existing models.

Another alternative account to consider for Experiments 2–4 is that our stimulus design confounded target–distractor similarity with our manipulation of distractor–distractor similarity. The reasoning here is that differences between the vertical and horizontal conditions shown in Figs 5 and 8 were not only in distractor–distractor similarity, but that the target was now also more similar to the second distractor in the vertical condition than to its counterpart in the horizontal condition. In this case, the more difficult search in the vertical condition would be attributed to the increased target–distractor similarity, not the decreased distractor–distractor similarity.

However, this reasoning leads again to a puzzle we have already mentioned. Namely, why did target–distractor similarity have a larger effect in Experiment 1 than in Experiments 2–4, if the same principles were involved? Yet it is worth considering experiments in which this potential confound might be controlled. One way might be to compare the 'strength' of two possible sources of grouping, say, grouping by color *vs.* by symmetry. For example, in a search involving a red target shape among red distractors that share symmetry and blue distractors that are identical in shape to the target, it is possible to provide incentives for considering only a subset of the items. This can be done by varying the relative proportions of the two distractors so that subset search efficiency can be measured for selection by either symmetry or color. If subset selection based on symmetry is comparable to that based on color it would add to the evidence that perceptual interactions among items in search are not restricted to simple intensive (e.g. luminance, color) or even geometric (e.g. orientation, curvature) visual properties. These variations in distractor–distractor similarity would also not be confounded with variation in target–distractor similarity.

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