Research Article

New Reflections on Visual Search

Interitem Symmetry Matters!

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ABSTRACT—*A 90° rotation of a display can turn a relatively easy visual search into a more difficult one. A series of experiments examined the possible causes of this effect, including differences in overall item shape and response mapping (Experiment 1), the interpretation of scene lighting (Experiment 2), the axis of internal symmetry of the search items (Experiment 3), and the axes of interitem symmetry between target and distractor items (Experiment 4). Only the elimination of differences in interitem mirror symmetry resulted in equal search efficiency in the upright and rotated displays. This finding is strong support for the view that visual search is guided by an analysis that considers interitem relations.*

A simple rotation of a display can have a profound effect on the efficiency of visual search (Olson & Attneave, 1970). The search task in Figure 1a is easier than that in Figure 1b (Enns & Kingstone, 1997; Heathcote & Mewhort, 1993). This is puzzling because the two displays differ only in that the target and distractor items in Figure 1a have been rotated clockwise by 90° to create the display in Figure 1b. Yet, in one study, the average time to detect the target was more than 250 ms longer in displays such as Figure 1b than in displays such as Figure 1a (Enns & Kingstone, 1997).

According to the feature-integration theory, the efficiency of search depends greatly on whether the target differs from the distractors by a single feature or a combination of features (e.g., Treisman & Gelade, 1980). Although feature search is generally more efficient than conjunction search, search for conjunction targets can be made equally efficient if it is possible to inhibit distractor items sharing one of the features of the target item (Treisman & Sato, 1990).

In contrast to the idea that search efficiency is influenced by the inhibition of individual items on the basis of a single feature, Duncan and Humphreys's (1989, 1992) theory emphasizes perceptual groupings, based on visual similarity, among items within a display. Supporting evidence is found in studies in which search for target items is more difficult when they share common motion direction and phase with distractor items (Driver, McLeod, & Dienes, 1992; Kingstone & Bischof, 1999).

We noted that the upright and rotated search displays in Figure 1 differ in at least four ways. Three of these differences involve properties of individual items, so finding that one of these is responsible for the differences in search efficiency would support feature-integration theory. Only the fourth difference involves possible perceptual grouping among the display items; finding that it is responsible for the differences in search would support the grouping theory. First, rotation of a display changes the shape of the individual items from tall to wide rectangles. Second, there is a change in the interpreted lighting source, from top lighting in the upright display to side lighting in the rotated display. Third, the items in Figure 1a are internally symmetric about the vertical axis, whereas the items in Figure 1b are internally symmetric about the horizontal axis. And fourth, targets and distractors in Figure 1a are related to one another by a mirror reflection about the horizontal axis, whereas targets and distractors in Figure 1b are related to one another by a mirror reflection about the vertical axis. Search in an upright display therefore involves finding a target that is unique in its top and bottom; search in a rotated displays involves finding a target that is unique in its left and right sides. We report four experiments that tested the influence of these factors on search efficiency.

EXPERIMENT 1: ITEM SHAPE AND RESPONSE MAPPING

There are two reasons why it may be easier to search among tall than among wide items in these displays. First, in general, it may be easier to search among tall items than among wide items because wide objects tend to span both visual fields, which leads to interhemispheric competition (Enns & Kingstone, 1997; Fecteau, Enns, & Kingstone, 2000). Second, search may be generally easier in the upright displays than in the rotated

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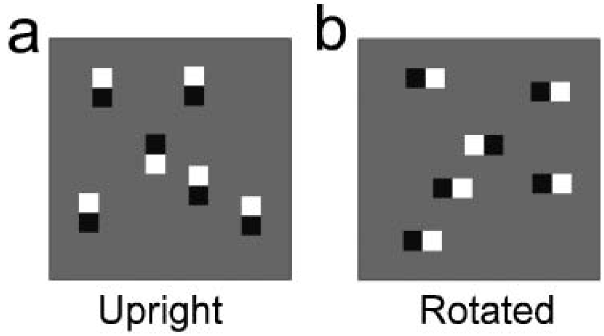

Fig. 1. Two search displays that differ only by a clockwise rotation of 90° (from Enns & Kingstone, 1997). It is easier to find the black-top target among the white-top distractors (a) than to find the black-right target among the white-right distractors (b). Turning the page upside down reveals a search asymmetry in (a): It is easier to find black-top targets among white-top distractors than to find white-top targets among black-top distractors. There is no such asymmetry in (b): black-left and black-right targets are equally difficult to find.

displays because the items in the upright displays differ only in their tops and bottoms, rather than in their left and right sides. Research has shown that human adults, human infants, and even octopi find top-bottom discriminations of all kinds generally easier to learn than left-right discriminations (Sutherland, 1960).

To test these alternatives, we used the three types of displays shown at the top of Figure 2: (a) the displays used in previous research (Enns & Kingstone, 1997), in which upright displays happened to consist of tall items and rotated displays consisted of wide items; (b) displays in which the upright version consisted of wide items and the rotated version consisted of narrow items; and (c) displays with square items. If search for tall items is generally easier than search for wide items, then search efficiency for the rotated displays with tall items should be better than search efficiency for the upright displays with wide items (Fig. 2b), and there should be no search difference for upright versus rotated displays of square items (Fig. 2c). Alternatively, if search in upright displays is generally easier than search in rotated displays, then there should be no difference in search efficiency across these three types of displays (i.e., the upright displays in each case should be searched more efficiently than the rotated displays).

In addition to assessing the influence of item shape on search performance, we used Experiment 1 to rule out the possibility that response mapping played a role in the search differences obtained previously. In our earlier study (Enns & Kingstone, 1997), observers indicated whether the target appeared on the left or right of the screen. It is possible that this response mapping was more compatible with upright than with rotated displays. We used two groups of participants to test this idea. Although they responded to identical search displays, one group indicated target location with a top-bottom response mapping and the other indicated target location with a left-right response mapping.

Method

Participants

Forty-five participants were randomly assigned to one of two response-mapping groups (left-right or top-bottom). Each participant searched in all combinations of the three display types (see Figs. 2a–c) and two orientations (upright, rotated), in separate blocks of trials. Two specific target-distractor pairs were tested in each of these six display conditions (upright displays: black-top target and white-top distractors or white-top target and black-top distractors; rotated displays: black-left target and white-left distractors or white-left target and black-left distractors). Set size (8, 16, or 24 items) varied randomly between trials within a block. The order of these 12 combinations of display condition and target-distractor pair was determined randomly, with the restriction that successive blocks of trials did not involve either the same display type or the same target type (e.g., two white-top targets in succession). Each participant completed 120 trials in each of the conditions, with a rest break occurring every 24 trials.

Displays

The computer screen was divided into an imaginary grid of 9 columns and 6 rows. Items could not appear on the vertical meridian of the grid, leaving 48 possible item locations. The center-to-center distance between grid locations was 1.8° visual angle. Between trials, items were randomly jittered by 0.2° within each grid location to avoid influences of item collinearity. Items subtended 0.94° on average, with the maximum height or width being 1.4° and the minimum being 0.7°.

Procedure

Participants sat approximately 57 cm from the screen in a dimly lit room. Each trial began with the presentation of a small central fixation dot (0.5°), which remained present for the entire trial. The search display was presented 675 ms after the onset of the dot and remained on the monitor until a response was made or 6 s had elapsed.

Participants responded with a speeded key press. Participants in the left-right response-mapping group pressed "z" when the target was on the left and "/" when it was on the right. Participants in the top-bottom response-mapping group had the keyboard rotated 90° counterclockwise, and pressed "z" when the target was below the fixation point and "/" when the target was above the fixation point. Participants were instructed to respond as quickly as possible without committing more than 10% errors overall. Three participants in the left-right group made errors on more than 20% of the trials and were excluded from the analyses.

Results and Discussion

Mean correct response time (RT) and mean percentage errors for each of the 12 conditions are shown in Figure 2. The overall error

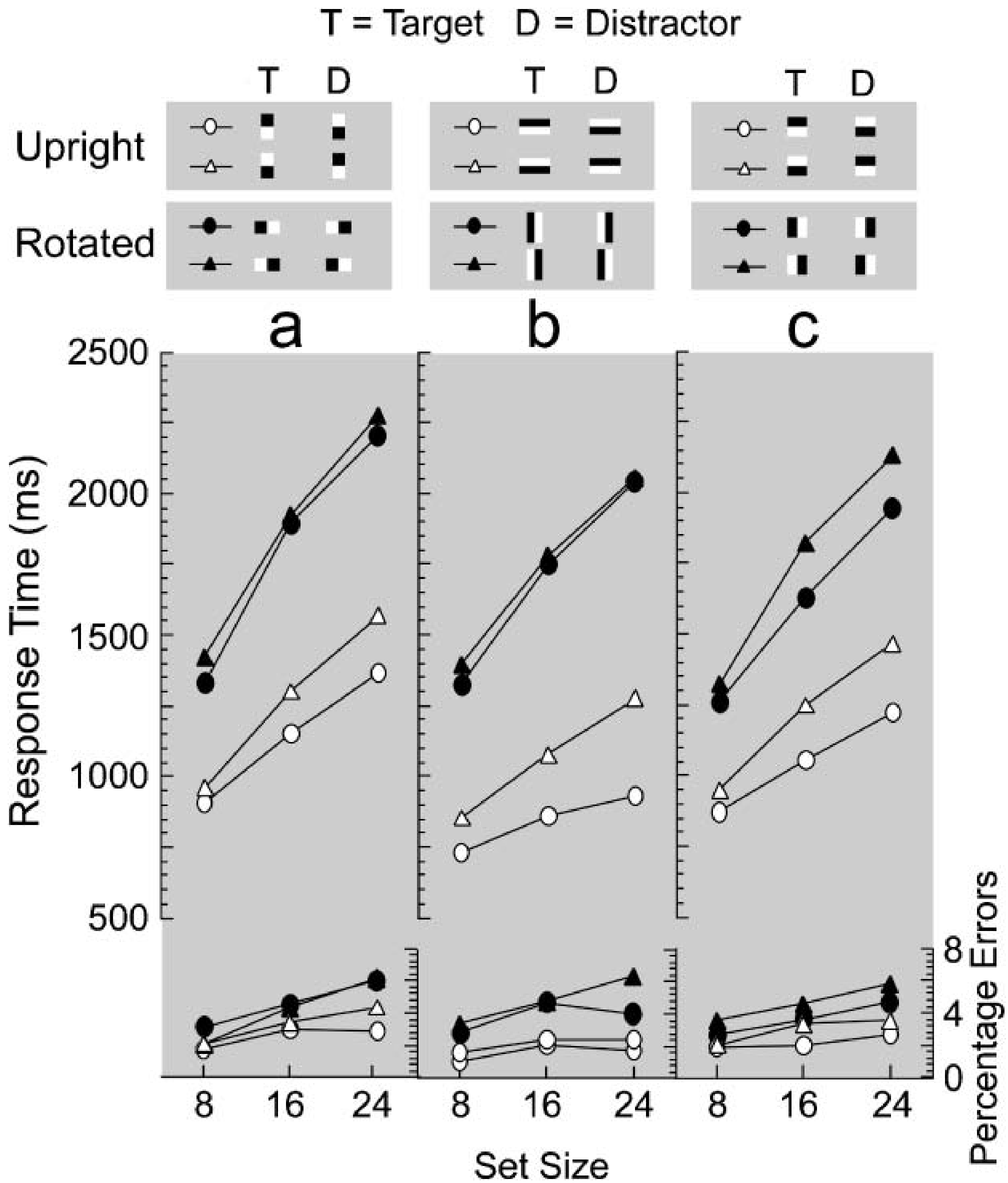

Fig. 2. Search items and results from Experiment 1. The illustrations at the top show the 12 combinations of display condition and target-distractor pairs (two target types in each display condition). The display conditions were created by the combination of three display types (as shown in a, b, and c) and two display orientations (upright and rotated). See the text for further details. The graphs present mean correct response time and mean percentage of errors. Results are collapsed over the two response-mapping groups (left-right, top-bottom).

rate was low in this and the subsequent experiments, and results of statistical analyses of the errors never contradicted results of analyses of the RT data; consequently, we focus on the analyses of the RT data.

RT was examined with an analysis of variance involving display type (see Figs. 2a, 2b, and 2c), response mapping (top-bottom, left-right), display orientation (upright, rotated), target type (upright: white-top target, black-top target; rotated: white-left target, black-left target), and set size (8, 16, 24). Search in all the display types was attention demanding, as indexed by increased RT with increased set size, $F(2, 80) = 494.88, p < .001$, $p_{rep} > .99$, $\eta^2 = .86$, but was not affected by response mapping in any way (no significant main effect or interaction with any other factor). There was also no significant main effect of display type, and display type did not interact with any other factor, $F(4, 160) = 2.21, p > .05, p_{rep} = .85, \eta^2 = .05$, indicating that the shape of the individual items was not important in determining search efficiency. In contrast, display orientation was a critical factor: Search was faster in upright than in rotated displays, $F(1, 40) = 315.03, p < .001, p_{rep} > .99, \eta^2 = .89$.

A secondary finding evident in Figure 2 is that the two target-distractor pairs resulted in very similar search in rotated displays, but not in upright displays. In upright displays, search was always faster for black-top than for white-top targets, F(1,

40) = 39.52, $p < .001$, $p_{rep} > .99$, $\eta^2 = .50$. These differences resulted in a three-way interaction among display orientation, target-distractor pair, and set size, $F(2, 80) = 12.74$, $p < .001$, $p_{rep} > .99$, $\eta^2 = .24$. Variation in search efficiency when the roles of target and distractor items are reversed is often referred to as *search asymmetry* in the visual search literature. It is taken as an index of which features are "marked" by the visual system (Treisman & Gormican, 1988). In this case, the results are consistent with the expectation of lighting from above the scene, such that a black-top target among white-top distractors looks "odd" and stands out more than a white-top target among black-top distractors.

The results of Experiment 1 rule out the possibility that item shape or response mapping underlies differences in search efficiency for the two kinds of displays illustrated in Figure 1. Next, we turn to the possible role of the interpreted scene lighting in these displays, in which the upright displays appear to be lit from above and the rotated displays appear to be lit from the side.

EXPERIMENT 2: DIRECTION OF LIGHTING

Considerable evidence suggests that human vision is biased to interpret surfaces as being lit from overhead (Aks & Enns, 1992; Ramachandran, 1988). A bias for overhead lighting could explain why search is easier for the kind of display depicted in Figure 1a, in which the items can be interpreted as being lit from above, than for the kind of display depicted in Figure 1b, in which one would have to assume that the light source is on one side. Such a bias would also explain why the search asymmetry in Experiment 1 favored displays with targets that were black on top among distractors that were white on top, because those targets ran against the standard expectation of an overhead light source (Kleffner & Ramachandran, 1992; Ramachandran, 1988).

If the direction of lighting is an important influence on search in the displays illustrated in Figure 1, then removing differences in the interpreted direction of lighting should attenuate the differences in search efficiency. In Experiment 2, we tested this prediction by designing displays that did not permit a lighting interpretation. Critically, these displays, which are depicted at the top of Figure 3, involved the same display orientations (upright vs. rotated) as the displays in Experiment 1, but in this case search could not be based on lighting direction and instead had to be based on the spatial pattern internal to the items.

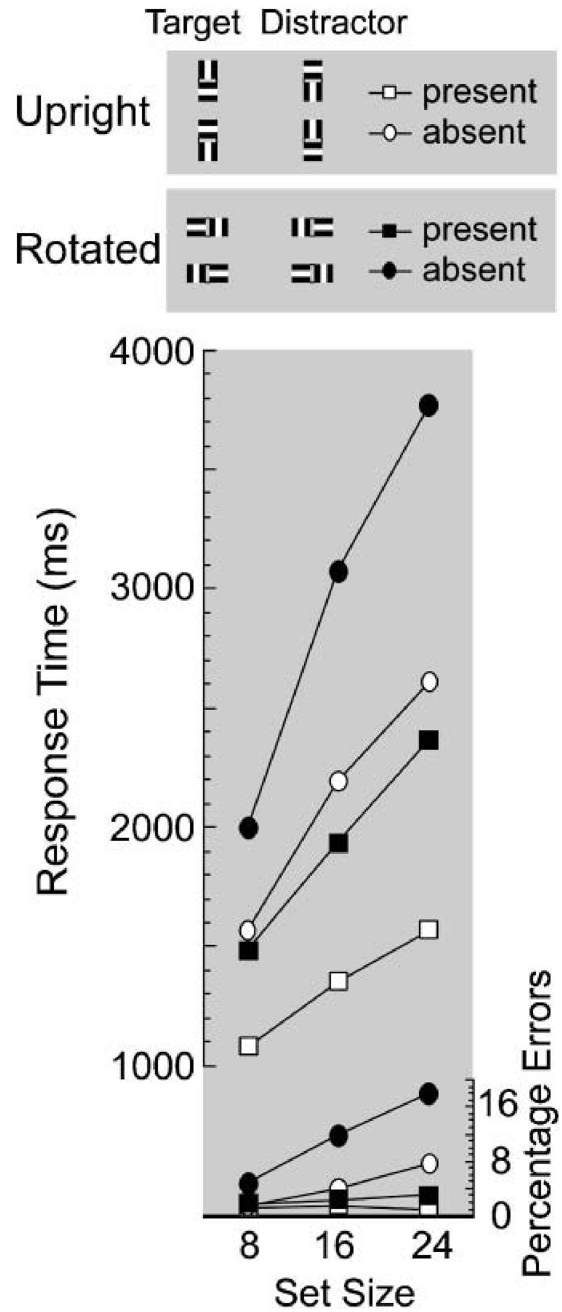

Fig. 3. Search items and results from Experiment 2. The illustrations at the top show the two target-distractor pairs used in each display orientation (upright, rotated). The graph presents mean correct response time and mean percentage of errors separately for target-present and target-absent trials for each display orientation. The results are collapsed across the two target-distractor pairs in each display orientation.

Method

Twenty-four undergraduate students at the University of British Columbia participated in a 1-hr session for extra course credit. The method was similar to that of Experiment 1, with the exception that the target was present on only half the trials. The task was to indicate whether the target was present or absent by pressing one of two keys—"z" or "/," with the key assigned to "present" counterbalanced across participants. Participants searched in the two display orientations (upright vs. rotated) in a counterbalanced order. For each participant, one target-distractor pair was randomly selected to be used for each display orientation (see Fig. 3). Each participant was tested on a total of 300 trials in each condition, with a rest break occurring every 30 trials.

Results

Figure 3 presents mean correct RT and mean percentage errors as a function of set size. Overall, RT increased with set size, $F(2, 46) = 301.22, p < .001, p_{rep} > .99, \eta^2 = .93$, and RT was longer on target-absent trials than on target-present trials. There was a strong interaction between set size and target presence. Set size had a greater effect on target-absent trials than on target-present trials, $F(2, 46) = 122.53, p < .001, p_{rep} > .99, \eta^2 = .84$.

There are two key results. First, search was faster for upright displays than for rotated displays, $F(1, 23) = 45.00, p < .001, p_{rep} > .99, \eta^2 = .66$. Second, there was a significant interaction among display orientation, target presence, and display set size, $F(2, 46) = 10.04, p < .001, p_{rep} = .99, \eta^2 = .30$, such that the greater efficiency of search in upright displays relative to rotated displays was more pronounced for target-present trials (search slopes of 31 ms/item for upright and 55 ms/item for rotated displays) than for target-absent trials (search slopes were 65 ms/item for upright and 111 ms/item for rotated displays).

These results demonstrate that when there is no lighting interpretation possible, there is no longer a search asymmetry for upright items (the two target-distractor pairs within each display orientation led to equally efficient search). However, this experiment did not eliminate differences in search efficiency for upright versus rotated displays. Therefore, the present experiment rules out a role for the interpreted direction of lighting in mediating the differences in search efficiency between upright and rotated displays. This leaves two factors standing, and both pertain to the role of item symmetry. We looked first at the role of internal object symmetry.

EXPERIMENT 3: INTERNAL ITEM SYMMETRY

Human vision is very sensitive to internal item symmetry in tasks such as object detection (Olivers & van der Helm, 1998) and pattern matching (Hershenson & Ryder, 1982; Sebrechts & Garner, 1981). It is also well established that sensitivity to internal item symmetry is greater for mirror reflections about the vertical than the horizontal axis (Palmer & Hemenway, 1978; Tyler, 2002). The items in Figure 1a are internally symmetric about the vertical axis, whereas the items in Figure 1b are symmetric about the horizontal axis. This leaves open the possibility that search in the upright displays is more efficient than search in the rotated displays because of their respective internal symmetry. If so, then removing internal symmetry should equate search efficiency for the two display orientations.

Method

Twenty-four undergraduate students participated in a 1-hr session for extra course credit or for remuneration. All participants had normal or corrected-to-normal vision. The search items are shown in Figure 4a. They are similar to those in Experiment 2, except that the internal details have been moved so that the items no longer have internal symmetry. Participants completed five blocks of 30 test trials; for each participant, one target-distractor pair was randomly selected for each display orientation (see Fig. 4a). Order of display orientation (upright, rotated) was counterbalanced.

Results

Figure 4a shows correct RT and percentage errors. RT increased with set size, $F(2, 46) = 142.06, p < .001, p_{rep} > .99, \eta^2 = .86$, and was longer for target-absent than for target-present trials, $F(1, 23) = 221.69, p < .001, p_{rep} > .99, \eta^2 = .91$. Set size had a more severe effect on target-absent trials than on target-present trials, $F(2, 46) = 80.45, p < .001, p_{rep} > .99, \eta^2 = .78$. Search was overall faster in the upright displays than in the rotated displays, $F(1, 23) = 14.23, p < .001, p_{rep} = .99, \eta^2 = .38$, but most important, this main effect was qualified by an interaction between display orientation and set size: Search in the upright condition was more efficient than search in the rotated condition, $F(2, 46) = 15.42, p < .001, p_{rep} > .99, \eta^2 = .39$. Search slopes for target-present displays were 21 ms/item for upright items and 30 ms/item for rotated items; search slopes for target-absent displays were 49 ms/item and 67 ms/item, respectively. The three-way interaction of display orientation, target presence/absence, and set size was not significant, $F(2, 46) = 1.97$. $p > .1, p_{rep} = .76, \eta^2 = .08$.

Eliminating differences in internal symmetry associated with the items in upright and rotated displays did not eliminate differences in search efficiency between the two display orientations. The only remaining explanation to be considered is that the difference in search efficiency is due to interitem (target-distractor) symmetry. We explored this alternative in the final experiment.

EXPERIMENT 4: INTERITEM SYMMETRY

Previous studies have found that shapes that are identical when reflected across the vertical axis (e.g., b and d) are perceived as more similar to one another than shapes that are identical when reflected across the horizontal axis (e.g., b and p; Cairns & Steward, 1970; Rudel & Teuber, 1963; Sutherland, 1960; Wolfe & Friedman-Hill, 1992). In our previous experiments, the pairs of search items that constituted the target and the distractors were identical when reflected across either the horizontal axis (in upright displays) or the vertical axis (in rotated displays). This suggests that the search items may have been perceived as less similar to each other in the upright than in the rotated displays. It is intuitively clear that the search for a target becomes easier as the difference between the target and the distractors becomes greater (Duncan & Humphreys, 1989; Duncan & Humphreys, 1992; Wolfe & Friedman-Hill, 1992). Therefore, we predicted that if interitem symmetry about either axis was removed from both upright and rotated displays, then differences in search efficiency between the displays would be eliminated.

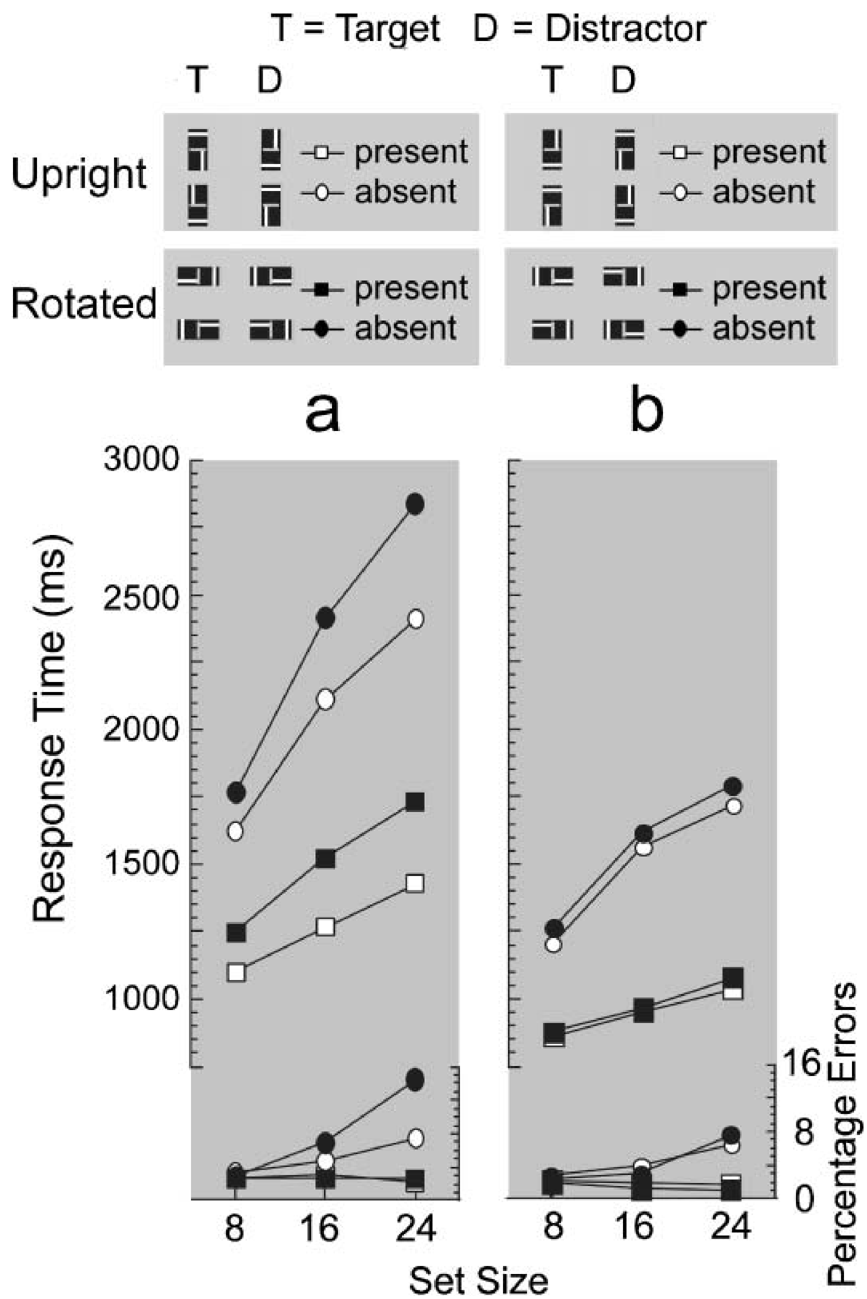

Fig. 4. Search items and results from (a) Experiment 3 and (b) Experiment 4. The illustrations at the top show the two target-distractor pairs used in each display orientation (upright, rotated) for each experiment. The graphs present mean correct response time and mean percentage of errors separately for target-present and target-absent trials for each display orientation. For each experiment, the results are collapsed across the two target-distractor pairs in each display orientation.

Method

Twenty-four undergraduate students participated in a 1-hr session for extra course credit or for remuneration. All had normal or corrected-to-normal vision. The search items are shown in Figure 4b. They are similar to those in Experiment 3, except that the internal details have been moved so that the items no longer share any interitem mirror symmetry (in addition to not having any internal symmetry).[1] The procedure was otherwise identical to that of Experiment 3.

[1]This study is limited to a consideration of axial mirror symmetry. Note that although the targets and distractors in Experiment 4 (Fig. 4b) were related by rotational symmetry (a 180° rotation in the plane), this was true for both the upright and the rotated displays. Thus, although rotational symmetry may be assessed by the visual system, it cannot explain why there was no difference between search in the upright and rotated displays in Experiment 4.

Results

Figure 4b shows correct RT and percentage errors. As in the previous experiments, RT increased with set size, $F(2, 46) = 80.85$, $p < .001$, $p_{rep} > .99$, $\eta^2 = .78$; RT increased when the target was absent, $F(1, 23) = 97.52$, $p < .001$, $p_{rep} > .99$, $\eta^2 = .81$; and set size had a more severe effect on target-absent trials than on target-present trials, $F(2, 46) = 35.41$, $p < .001$, $p_{rep} > .99$, $\eta^2 = .61$. However, unlike in each of the previous experiments, there was no main effect of display orientation (upright vs. rotated; $F < 1$). Further, search efficiency did not change as a function of display orientation ($F < 1$). Search slopes for target-present displays were 11 ms/item for upright and 12 ms/item for rotated displays, and search slopes for target-absent displays were 31 ms/item and 33 ms/item for upright and rotated displays, respectively (Fs < 1 for all interactions with display orientation). Therefore, removing all differences in interitem symmetry between upright and rotated search displays abolished all differences in search efficiency.

GENERAL DISCUSSION

The puzzling difference in visual search efficiency between the items in Figure 1a and Figure 1b can now be understood as a consequence of the interitem symmetry between items designated as targets and distractors. In Figure 1a, the target and distractors differ by mirror reflection across a horizontal axis of symmetry, whereas in Figure 1b, the target and distractors differ by reflection across a vertical axis of symmetry. The differences in visual search efficiency can be understood through the following chain of logic: First, interitem symmetry across the vertical axis results in pairs of items that are perceptually more similar to one another than does interitem symmetry across the horizontal axis (Cairns & Steward, 1970; Rudel & Teuber, 1963; Sutherland, 1960). Second, the similarity among targets and distractors in a visual search task has a direct influence on search efficiency, with targets being found more easily the less similar they are to distractors (Duncan & Humphreys, 1992). Third, interitem symmetry has an indirect influence on visual search efficiency through its effects on visual similarity (Roggeveen, Kingstone, & Enns, 2004).

We began this study by noting that interitem symmetry was not the only factor that could have created differences in search efficiency in the conditions exemplified in Figures 1a and 1b. Other differences included the shape of the items (tall vs. wide), the spatial mapping of target location in the search task to response keys, the interpretation of lighting direction, and the internal symmetry of the spatial pattern in each item. Eliminating each one of these factors in turn did not abolish the advantage in search efficiency for upright over rotated displays. This advantage was still robust in Experiment 1 after overall shape and response mapping had been controlled (Fig. 2), and it was still present in Experiment 2 after perceptual interpretations based on lighting direction had been eliminated (Fig. 3). Even eliminating differences in internal item symmetry in Experiment 3 did not result in equal search efficiencies for upright and rotated displays (Fig. 4a). It was only when the differences in interitem mirror symmetry were abolished in Experiment 4 that search efficiency no longer differed between the two kinds of display orientations (Fig. 4b). The present results indicate that search is guided by an analysis of the display that takes interitem relations into account.

This conclusion is not easy to accommodate within the well-known feature-integration theory and its variants (Treisman & Gelade, 1980; Treisman & Sato, 1990; Wolfe, Cave, & Franzel, 1989; Wolfe, 1994). These theories propose that the visual system parses each search display into topographic neural maps according to simple visual features that are registered at each location. Search may then be based on a process of either selective inhibition of distractor items sharing one feature with the target (Treisman & Sato, 1990) or selective excitation of items sharing the specified features of the target (Wolfe et al., 1989; Wolfe, 1994).

The present results, along with those of Roggeveen et al. (2004), show that visual search is influenced by rather abstract spatial relations such as interitem symmetry. Such results are difficult to accommodate within the proposed spatially local processes of feature-integration theory. Rather, the results support a view according to which search is accomplished by a series of recursive, spatially parallel comparisons between a target template and all items in the visual display. In this internal process, weights are assigned to all the items in a display on the basis of their similarity to the search image and to one another (Duncan, 1985, 1993). Thus, the more similar a distractor is to the target, the greater the number of recursive steps that will be needed to differentiate the target from the distractors. Distractors will also tend to be grouped with one another through the spreading activation that occurs for similar items. In this theory, the finding that interitem symmetry has an influence on visual search, through its direct influence on the interitem relations among items in a display, is a natural consequence of the way the visual system is designed. The challenge for future researchers will be to determine which other visual properties are used in the evaluation of interitem similarity.

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