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# Attentional set for axis of symmetry in symmetry-defined visual search

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Olivers and van der Helm (1998) showed that symmetry-defined visual search (for both symmetry and asymmetry) requires selective spatial attention. We hypothesize that an attentional set for the orientation of a symmetry axis also is involved in symmetry-defined visual search. We conducted three symmetry-defined visual search experiments with manipulations of the axis of symmetry orientations, and performance was better when the axis orientations within the search array were uniform, rather than a mixture of two orientations, and the attentional set for the axis orientation could be kept. In addition, search performance when the target was defined by the presence of symmetry was equivalent to that when the target was defined by a difference of symmetry axis orientation. These results suggest that attentional set for axis orientation plays a fundamental role in symmetry-defined visual search.

The human visual system can easily detect visual bilateral (mirror) symmetry. An efficient and robust perception of symmetry has been demonstrated in many experimental studies (e.g., Barlow & Reeves, 1979; Julesz, 1971), and it has been hypothesized that the human visual system is equipped with a mechanism that processes symmetric patterns holistically. Symmetry is present everywhere in everyday scenes, especially in objects (both natural and artificial). The efficient perception of symmetry seems helpful in segmenting and recognizing visual objects (Parovel & Vezzani, 2002; Rock, 1983). But what is the relationship between the perception of symmetry and the visual attention that selects the object? If symmetry is automatically encoded in the early stage of visual processing, it is plausible that the mechanism precedes attentional selection. However, if the mechanism requires complex and mass processing of a symmetric pattern that comprises many distributed visual elements (e.g., dots in a dot pattern), it can be presumed to work at a late stage, after attentional selection.

The visual search experiments of Olivers and van der Helm (1998) provide one clear answer to the question: Symmetry search requires visual spatial attention. Olivers and van der Helm presented several patterns simultaneously and required their observers to search for one symmetric (asymmetric) pattern as a target among asymmetric (symmetric) distractor patterns. According to the feature integration theory of attention (Treisman & Gelade, 1980), if symmetry is a basic visual feature that is automatically encoded, it pops out. However, Olivers and van der Helm found inefficient (i.e., serial) search functions (Neisser, 1963; Treisman & Gelade, 1980): Longer response times were found for larger display sizes. Thus, the detection of symmetry within multiple patterns required attention's focusing on each pattern.

However, one question remained: What attribute was detected in such symmetry-defined visual search? In Olivers and van der Helm's (1998) experiments, the criterion that differentiated targets from distractors was the presence (or absence) of vertical symmetry. Hence, the targets could be found by detection of (1) vertical symmetry, (2) symmetry in general (i.e., coded as the presence of symmetry, irrespective of its axis orientation), or (3) asymmetry per se. A vertically symmetric target among asymmetric distractors can be determined by the presence of any vertical symmetry or symmetry in general or by the absence of asymmetry per se. An asymmetric target among vertically symmetric distractors can be determined by the absence of any vertical symmetry or symmetry in general or by the presence of asymmetry per se. Depending on the observer's attentional set for which kind of attributes should be detected, the performance of symmetry-defined visual search would be altered.

Which of these three attributes influenced the results of Olivers and van der Helm's (1998) symmetry-defined visual search? Even in their conditions of search for asymmetry, it is hard to imagine that the observers detected asymmetry per se, rather than symmetry. The asymmetric

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target might be found as a failure to detect symmetry. If the observers did not keep their attentional set for asymmetry per se, did they try to detect vertical symmetry or symmetry in general? Since all of the symmetric stimuli in Olivers and van der Helm's experiments had vertical symmetry, it can be hypothesized that their observers used an attentional set only for vertical symmetry.

Wenderoth (1994) reported evidence of such an attentional set specific for axis orientation. He required his observers to judge whether a single dot pattern was symmetric or not, while the orientation of the axis of symmetry was systematically manipulated as a within-block factor. Although the robust perceptual superiority of vertical symmetry over other axes is known (Barlow & Reeves, 1979; Rock & Leaman, 1963; Wenderoth, 1996), when possible axes were concentrated around the horizontal orientation (Wenderoth's [1994] Experiment 3), the performance for horizontal symmetry was much better than that for vertical symmetry. His interpretation of this attentional effect was that "subjects probably prepared for orientations closer to horizontal" (p. 233). Hence, this research suggests that an attentional set for the axis orientation improves the detection of symmetry for the attended axis and may even impair detection for the ignored axis.

In short, two different kinds of attentional processes seem to be involved in symmetry-defined visual search: selective attention, which serially focuses on the locations of items, as Olivers and van der Helm (1998) showed, and attentional set, which improves the detection of symmetry for an attended axis (Wenderoth, 1994). In our present study, we focused on the latter process. We hypothesized that an attentional set for an axis orientation plays an important role in symmetry-defined visual search. Although Olivers and van der Helm's visual search tasks required only decisions as to the presence or absence of symmetry, we hypothesized that the attentional set for (1) vertical symmetry, rather than for (2) symmetry in general or (3) asymmetry per se, determined their results.

To examine this hypothesis, we conducted three visual search experiments in which the effects of axis orientation were investigated. Experiment 1 involved visual searches with vertical symmetry and horizontal symmetry and was designed to investigate what attribute is detected in symmetry-defined visual search. Experiment 2 was designed to directly test the hypothesized improvement of visual search performance related to attentional set for axis orientation. It contrasted two distractor conditions: a uniform axes condition in which the axis orientations of the distractors were uniform and a mixed axes condition in which the distractors were a random mixture of vertical symmetry and horizontal symmetry. For the uniform axes condition, it was predicted that the attentional set for the uniform axis orientation would improve search performance. Experiment 3 involved axis-orientation-defined visual search in which both the target and the distractors were symmetric but differed in their axis orientations. The results were compared with those in Experiment 1 (symmetry/asymmetry-defined visual search) to ascertain whether an explicit perception of axis orientation was involved even in Experiment 1, which did not have a task requirement of deciding axis orientation. Through these experiments, we investigated the hypothesized involvement of attentional set for axis orientation in symmetry-defined visual search.

## GENERAL METHOD

### Design and Procedure

We conducted typical visual search experiments. One or more patterns were displayed, and the observers were required to search the display (search array) for the predetermined target. In the present study, the target and distractors (nontarget items) were defined in terms of symmetry. The definitions differed depending on the experimental condition (see the Method section for the respective experiments). The display size (the number of items making up the search array) was also varied. The search array included one target item in half of the trials (target-present condition) and no target in the other half of the trials (target-absent condition). The observers judged whether the target item was present or absent in the displayed search array and responded in a two-alternative forced choice manner by pressing an appropriate key. They were instructed to respond as quickly and accurately as possible. Reaction times (RTs) and error rates were measured as independent variables.

Each trial started with a 1,500-msec presentation of a fixation cross at the center of the screen. The observers were told to fixate on it when it appeared. Then the search array was displayed until the observer made a keypress response. Auditory feedback (100-msec beep sound of high or low tones) immediately followed in order to inform the observer whether the response was correct. After a 2-sec blank display, the next trial started automatically.

### Apparatus

All the experiments were run in a dimly lit room. The stimuli were displayed on a 20-in. CRT monitor (NANAO FlexScan E65T; refresh rate, 75 Hz). A computer program (MATLAB script) running on an Apple G3 personal computer generated the stimuli and controlled all the experiments. The observers sat and fixed their head in a chinrest 80 cm from the screen. They made responses by pressing either of two keys on the computer keyboard. Assignments of the two keys to responses were counterbalanced between observers.

### Stimuli

All the stimuli were black (0.9 $cd/m^2$) on a gray (35.5 $cd/m^2$) background. The search array was a circular arrangement of items around a fixation cross (see Figure 1A). The fixation cross was approximately $0.3^\circ \times 0.3^\circ$ in visual angle. Each item maximally subtended 1.0º in diameter, and its center was 1.75º away from the center of the fixation cross. The search array maximally subtended 4.5º in diameter. The items were arrayed with equal intervals on an imaginary circle, but their absolute positions were randomly changed for each trial. In target-present trials, one item was randomly selected as a target, and the others were distractors; all the items were distractors in target-absent trials. All the items within the search array differed from each other in shape.

The items were computer-generated novel polygons. An item possessed one of three possible attributes: vertical symmetry (V), horizontal symmetry (H), or asymmetry (A). All the items consisted of 12 apexes (see Figure 1B), 2 in each of the four quadrants (variable apexes) and 1 on each axis of the four directions (3, 6, 9, and 12 o'clock). The latter four apexes were always 0.4º away from the center of the item; that is, all the items shared those four (constant) apexes. This method excluded inordinately small or large shapes. It also ensured that the observers could not discriminate the three types of items (V, H, and A) by using local visual attributes, such as the presence of apexes on vertical or horizontal axes. For asymmetric items, two coordinates were randomly selected from each quadrant, with the constraint that they were maximally 0.5º and minimally 0.1º away from the center of the item. For vertically symmetric items, the coordinates of the apexes on the left half were reflected on the right half. For the horizontally symmetric items, the apexes in the

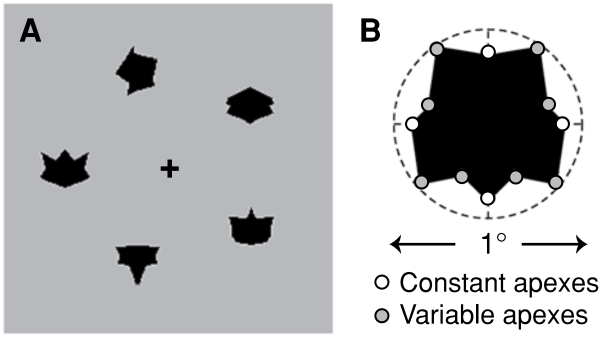


**Figure 1. (A) Example of the search array stimuli used in this study, containing one asymmetric target item. (B) Schematic representation of search item polygons, vertically symmetric in this example. White circles represent constant apexes that were shared by all the items, whereas the apexes of the gray circles were variable.**

upper half were reflected on the lower half. All the items were newly generated for each trial by the computer program.

## EXPERIMENT 1

The purpose of this experiment was to determine which attributes of items would be detected in a visual search task similar to that in Olivers and van der Helm (1998): (1) vertical symmetry, (2) symmetry in general, or (3) asymmetry per se. Two types of search tasks were used: search for a symmetric target among asymmetric distractors (symmetry condition) and search for an asymmetric target among symmetric distractors (asymmetry condition). In addition, the symmetry of the stimuli varied on two axis orientations: vertical and horizontal. Accordingly, the two factors of target symmetry and axis orientation produced four search conditions: symmetry conditions with vertical symmetry (VA) or with horizontal symmetry (HA) and asymmetry conditions with vertical symmetry (AV) or with horizontal symmetry (AH). Note that the first letter of these search condition names denotes the target and the second denotes the distractors. For convenience, we will utilize this rule of abbreviation throughout the present article. The VA and AV conditions are replications of the conditions in Olivers and van der Helm's experiments.

We were interested in how the effect of axis orientation would emerge in the symmetry condition and the asymmetry condition, respectively. If vertical symmetry or horizontal symmetry were detected to perform the visual search task, axis orientation should have an effect on search efficiencies. Many previous studies have demonstrated that vertical symmetry is easier to detect than horizontal symmetry (Barlow & Reeves, 1979; Rock & Leaman, 1963; Wenderoth, 1996). Correspondingly, VA and AV should yield better performances than do HA and AH. If asymmetry per se of the distractors (in the symmetry condition) or of the target (in the asymmetry condition) were detected to perform the task, axis orientation should not yield any effect, because vertical symmetry and horizontal symmetry would be equally influential for deciding the absence of asymmetry per se. If symmetry in general were detected, the symmetry condition would show no effect of axis orientation on search efficiencies, since the condition's asymmetric distractors would be judged on the basis of the absence of symmetry in general, independently of the axis orientations of the targets. The asymmetry condition might show some effect of axis orientation, such as better search in AV than in AH, because the bottom-up process of vertical symmetry detection might be faster even when symmetry in general was explicitly detected.

### Method

**Observers**. Twelve undergraduate and graduate students (including one of the authors) participated in this experiment. Their ages ranged from 19 to 24 years ($M = 21.8$). All had normal or corrected-to-normal vision.

**Design and Procedure**. All the observers performed all four of the search conditions, VA, HA, AV, and AH (target symmetry [symmetry or asymmetry condition] × axis orientation [vertical or horizontal]), in separated blocks. The orders of the four conditions were counterbalanced between observers. The presence of the target (present or absent) and display size (1, 3, 5, or 7) were randomly varied within a block. The observers' task was to decide whether the target was present or absent as quickly and accurately as possible. For each search condition, the observers performed a practice session (16 trials) and an experimental session (80 trials). The practice session was repeated until the error rate was less than 20%.

### Results

**Reaction time**. For each search condition and for each observer, we calculated mean RTs for trials with correct responses as a function of display size and then averaged them over observers (Figure 2). Exceptionally short (less than 200 msec) or long (more than 5,000 msec) RTs were treated as errors and were excluded from the RT analysis. All the search functions had positive slopes, which indicated serial searches. We conducted a four-way repeated measures ANOVA with the factors of target symmetry (symmetry condition or asymmetry condition), axis orientation (vertical or horizontal), target presence (present or absent), and display size (1, 3, 5, or 7). If vertical symmetry improved search efficiency (as shown by a gentle slope of search function) more than did horizontal symmetry, as we hypothesized, an effect of axis orientation and its interaction with display size would be observed. As a result, all the main effects were significant [$F(1,11) = 62.28$, $p < .001$, $F(1,11) = 23.54$, $p < .001$, $F(1,11) = 209.28$, $p < .001$, and $F(3,33) = 186.62$, $p < .001$, respectively]. Some interactions were also significant: target symmetry × target presence [$F(1,11) = 58.60$, $p < .001$], target symmetry × display size [$F(3,33) = 61.48$, $p < .001$], axis orientation × display size [$F(3,33) = 15.54$, $p < .001$], target presence × display size [$F(3,33) = 20.12$, $p < .001$], target symmetry × axis orientation × target presence [$F(1,11) = 5.86$, $p < .05$], and target symmetry × target presence × display size [$F(3,33) = 6.72$, $p < .01$]. The interaction of target symmetry and axis orientation approached significance [$F(1,11) = 4.77$, $p = .052$].

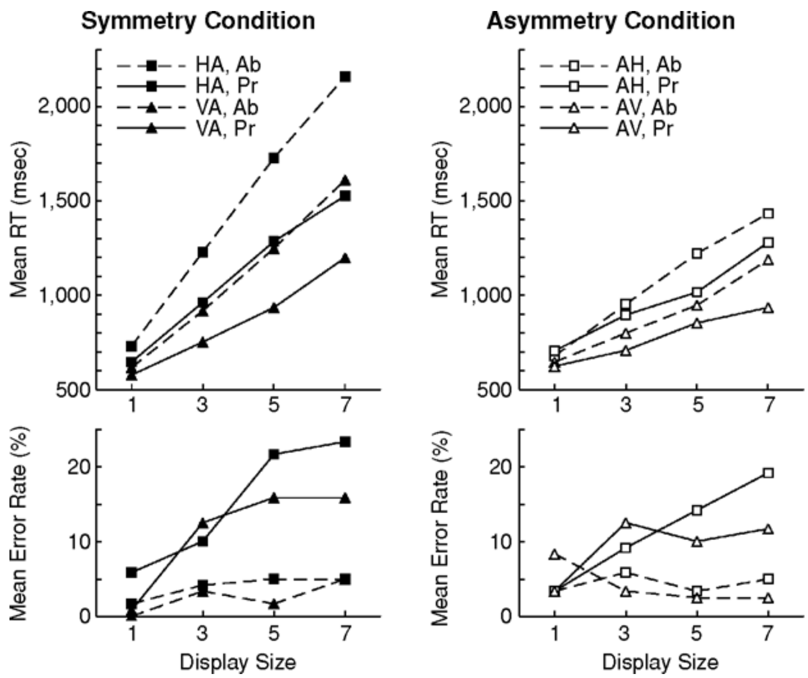


**Figure 2. Results of Experiment 1. Pr, target present; Ab, target absent. VA, HA, AV, and AH are the search conditions, indicating the target by the first letters, and indicating the distractors by the second letters. V, vertical symmetry; H, horizontal symmetry; A, asymmetry.**

The significant effect of display size confirmed the serial search function, yet the slopes of the search functions depended on the search conditions. The main effect of axis orientation and its interaction with display size revealed that search for vertical symmetry (VA and AV) was more efficient than that for horizontal symmetry (HA and AH). The axis orientation did not alter the qualitative nature of visual search, yet it did affect search efficiency. Target symmetry also showed a significant effect and an interaction with display size, reflecting steeper search functions in the symmetry condition than in the asymmetry condition. In other words, search asymmetry was observed: Swapping the target and the distractors changed search efficiency. This same tendency was reported by Olivers and van der Helm (1998). Search asymmetry will be discussed later.

The mean slopes of individually fitted search functions for target-present and target-absent conditions, respectively, were the following: VA, 102.4 and 165.5 msec/item; HA, 148.3 and 239.1 msec/item; AV, 54.1 and 88.8 msec/item; and AH, 92.4 and 126.7 msec/item.

**Error rate**. The mean error rate was calculated and analyzed (see Figure 2). The overall error rates were higher in target-present trials in proportion to the display size, suggesting that the errors were largely due to misses for the target. Consistent with the RT results, HA and AH yielded more errors than did VA and AV, respectively. The four-way ANOVA showed a significant main effect of axis orientation [$F(1,11) = 5.04, p < .05$], suggesting that performance in visual search was worse for horizontal symmetry than for vertical symmetry.

**Discussion**

The RT analysis provided evidence of a serial search function for all the conditions. This confirms the prior finding that symmetry perception requires selective spatial attention (Olivers & van der Helm, 1998).

**Effect of axis orientation**. Visual search was more efficient with vertically symmetric items than with horizontally symmetric items. The longer RTs for search for horizontal symmetry is explained as the accumulation of longer times for judging horizontal symmetry than vertical symmetry for each item. Note that in Experiment 1, the observers had no reason to have a bias in favor of the vertical axis in the search conditions HA and AH.

Most intriguingly, the axis orientations of the target stimuli affected search efficiency in the symmetry conditions (VA and HA), which shared the same (asymmetric) distractors. Especially in the target-absent trials, only asymmetric items were presented to the observers, and thus, there was no difference in the search arrays between VA and HA; still, search was faster in the VA condition than in the HA condition. This finding indicates that the search performances were affected by the observers' attentional set, as well as by the actually presented symmetric stimuli. Processing of asymmetric distractors was performed by the observers not on the basis of the detection of asymmetry per se, but on the basis of a failure to detect vertical or horizontal symmetry. Symmetry–asymmetry decisions, which were made irrespective of axis orientation, were not involved. The observers would have kept their attentional set for vertical symmetry in VA and for horizontal symmetry in HA, even though the task did not require decisions about axis orientation but only symmetry–asymmetry decisions. Consequently, we conclude that vertical symmetry and horizontal symmetry, respectively, rather than symmetry in general or asymmetry per se, were detected in the present experiment and, by implication, in Olivers and van der Helm's (1998) experiments.

**Symmetry condition versus asymmetry condition**. Target symmetry (symmetry condition or asymmetry condition) also affected search efficiency. Search was more efficient for an asymmetric target among symmetric distractors than for a symmetric target among asymmetric distractors. Such a difference of search efficiency between two conditions that swap the attributes of the targets and the distractors is known as *search asymmetry* (see Treisman & Gormican, 1988; Treisman & Souther, 1985; Wolfe, 2001). Olivers and van der Helm (1998) also found this search asymmetry. They interpreted the phenomenon as being a consequence of more rapid processing of symmetric shapes than of asymmetric shapes. Since the search for an asymmetric target is achieved as a result of the processing of symmetric distractors, it must be associated with relatively short RTs. This interpretation seems to be consistent with our conclusion that asymmetry per se was not detected, for a decision about an asymmetric item based on affirming the absence of symmetry may require more complex processing than does a decision about a symmetric item based only on perceiving its symmetry.

Incidentally, familiarity of search items is known to produce a similar search asymmetry. Search for an unfamiliar shape is easier than that for a familiar shape (Nothdurft, 1993; Richards & Reicher, 1978; Shen & Reingold, 2001). It is difficult, however, to assess the *familiarity* of the novel and nonsense patterns in the present and Olivers and van der Helm's (1998) experiments, although some commonality might underlie the two search asymmetries.

## EXPERIMENT 2

This experiment was designed to make possible a direct assessment of the involvement of an attentional set for axis orientation during symmetry-defined visual search. If such an attentional set is involved, vertical symmetry and horizontal symmetry will be detected by different attentional sets for the respective axis orientations. Imagine that observers have to decide whether a certain item is symmetric or asymmetric and that the item can have either vertical symmetry or horizontal symmetry but its axis orientation is unpredictable. Observers will have to set attention for one of the two possible axes and try to detect symmetry across the attended axis, at the cost of ignoring the other axis. Detecting symmetry about the ignored axis will require changing the attentional set. However, if the items' axes are aligned to one orientation and there are no unpredictable changes of the orientation, changing the attentional set will not be necessary. The attentional set for a predictable axis orientation will fully contribute to decisions about symmetry. Naturally, such cases will yield shorter RTs (or fewer errors).

The observers in this experiment were required to search for an asymmetric target among symmetric distractors. We planned and contrasted two distractor conditions within block. In the mixed axes condition, the distractors in the search array were a mixture of vertically symmetric items and horizontally symmetric items. In the uniform axes condition, the axis orientations of the distractors in the search array were uniform (aligned to the vertical or the horizontal). The observers had to search for a single asymmetric target and, hence, make decisions of symmetry for every distractor, although the axis orientation per se was irrelevant to the task. If attentional set for axis orientation was involved, the uniform axes condition would be expected to produce faster (or more accurate) searches than the mixed axes condition, because the mixture of axes would entail a cost of changing the attentional set for axis orientation.

### Method

**Observers**. Twelve undergraduate and graduate students (including one of the authors) participated in this experiment. They were 21 to 26 years of age ($M = 23.4$) and had normal or corrected-to-normal vision.

**Design and Procedure**. This experiment was designed with independent variables of distractor condition (mixed axes or uniform axes), target presence, and display size (3, 5, or 7). Two distractor conditions (50% of the trials for each) were randomly ordered within a session. In the mixed axes condition trials, the distractors consisted of vertically symmetric items and horizontally symmetric items. Since the display sizes were odd numbers, the target present array contained an equal number of the two axis orientations. For the target-absent array, a vertically symmetric or horizontally symmetric distractor (50% of the trials for each) replaced an asymmetric target item. In the uniform axes condition trials, the distractor items were all vertically symmetric in 50% of the trials (called uniform-V) or all horizontally symmetric in the other trials (uniform-H). Each observer completed a practice session (24 trials) and two experimental sessions (120 trials each). The observers were told that the target item was always asymmetric. The other procedures were identical to those in Experiment 1.

### Results

We discarded the data for 1 observer, whose error rate for any one of the distractor conditions was above 20%. The results from the other 11 observers (Figure 3) were analyzed as follows.

**Reaction time, mixed versus uniform**. Mean RTs for trials with correct responses were computed in the same manner as in Experiment 1. The data were analyzed with a three-way repeated measures ANOVA (distractor condition × target presence × display size). The main effect of distractor condition and its interaction with display size were expected, since we hypothesized greater search efficiency in the uniform axes condition. All the main effects were significant: RTs were shorter for the uniform axes condition than for the mixed axes condition [$F(1,10) = 77.36$, $p < .001$], shorter for target present than for target absent [$F(1,10) = 41.99$, $p < .001$], and increased with display size [$F(2,20) = 89.70$, $p < .001$]. The latter two effects reflect a serial search process, consistent with the asymmetry condition in Experiment 1. RTs were significantly shorter in the uniform axes condition, providing evidence of relatively efficient visual search when the distractors' axis orientations were uniform and predictable.

The interactions were also significant. The interaction between distractor condition and display size [$F(2,20) = 9.01, p < .01$] suggested that the RT decrements in the uniform axes condition were dependent on (and probably proportional to) display size. Thus, the decrements reflected the cumulative effect of the processing of individual items. The interaction of target presence and display size [$F(2,20) = 34.15, p < .001$] indicated more efficient search in the target-present trials because of the termination of the search when the target had been found, again corroborating a serial search process. A significant interaction between distractor condition and target presence was also observed [$F(1,10) = 17.28, p < .01$]. No other interaction was significant. The mean slopes for the mixed axes condition were 79.7 msec/item (target present) and 158.9 msec/item (absent). For the uniform axes condition, the mean slopes were 56.2 msec/item (present) and 114.4 msec/item (absent).

**Reaction time, separating uniform-V and -H**. We predicted that uniform-V distractors would be searched in a shorter time than uniform-H distractors, since in Experiment 1 the AV search was faster than the AH search. We separated the data for the uniform axes condition into uniform-V and -H and analyzed them along with the mixed axes condition in a three-way repeated measures ANOVA, with the factors of distractor condition (mixed, uniform-V, or uniform-H), target presence, and display size. There were significant main effects for the factors of target presence and display size [$F(1,10) = 34.99, p < .001$, and $F(2,20) = 90.88, p < .001$, respectively]. The distractor condition also yielded a significant main effect [$F(2,20) = 54.08, p < .001$]. Post hoc analyses (Tukey's HSD) showed that all the comparisons among the three distractor conditions were significant ($p < .01$). Therefore, the uniform-V condition required shorter RTs than did the uniform-H condition, replicating the results for the AV and AH conditions in Experiment 1. In addition, the mixed axes condition was found to have longer RTs than the uniform-H condition, even though it contained vertically symmetric distractors. This result further supported the interpretation that the mixture of axis orientations produced some cost in the visual search for asymmetry. Other significant effects were observed for the following interactions: distractor condition × target presence [$F(2,20) = 4.99, p < .05$], distractor condition × display size [$F(4,40) = 6.45, p < .001$], and target presence × display size [$F(2,20) = 27.38, p < .001$].

**Error rate**. Following the same procedure as that for the RT analysis, we performed the two ANOVAs using the error rate data. No significant difference between the mixed and the uniform axes conditions was found. The uniform-H condition produced a higher error rate than did the uniform-V condition and the mixed axes conditions (Tukey's HSD post hoc analysis of the main effect of distractor condition, $p < .01$). This tendency is consistent with the RT results.

## Discussion

This experiment showed clear evidence that uniform and predictable axis orientations facilitate symmetry-defined vi-

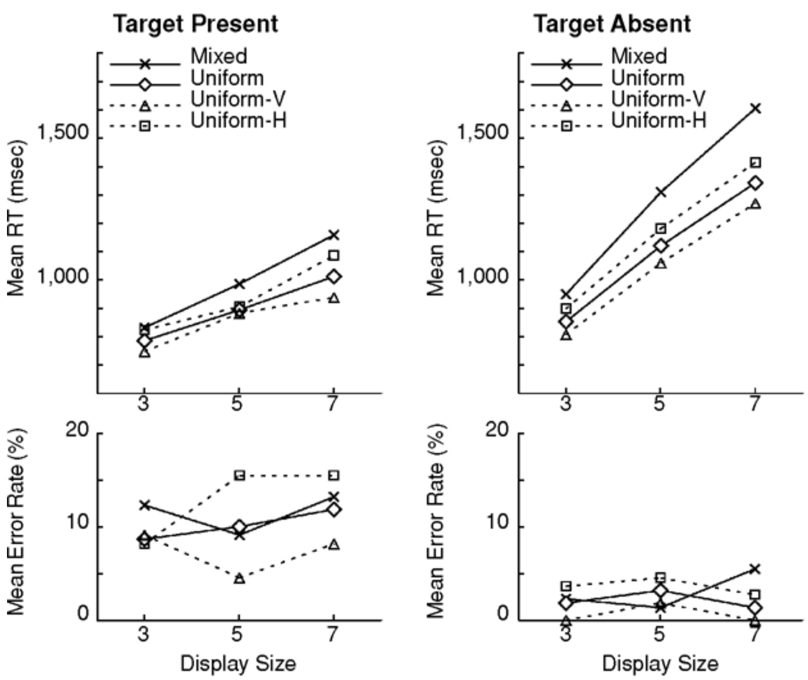


**Figure 3. Results of Experiment 2. Graph symbols represent the distractor conditions. Note that the results for the uniform axes conditions consist of the results for the conditions in which the distractors were vertically symmetrical (uniform-V) and those for the conditions in which the distractors were horizontally symmetrical (uniform-H).**

sual search. This effect was interpreted as being the result of the benefit of an attentional set for axis orientation. In other words, a random mixture of axis orientations corrupted the benefit and yielded a cost of changing the attentional set for other possible axis orientations. In fact, several observers in this experiment reported introspectively that they felt that the task with uniform-V distractors was relatively easier or that the task with mixed axes distractors was more difficult; thus, they explicitly processed axis orientations even though the task itself did not ask them to do so. The resulting RTs in the uniform-V and uniform-H conditions seemed to be roughly equal to those in the AV and AH conditions, respectively, in Experiment 1. Note that the search arrays were equivalent between the uniform-V and the AV conditions and between the uniform-H and the AH conditions. Thus, we speculate that the observers in Experiment 2 had a tendency to keep their attentional set for one axis, rather than changing it occasionally. Such a tendency should accentuate the observed advantage of the uniform axes condition.

The disadvantage in the mixed axes condition reported here is similar to an effect of stimulus similarity in visual search (Duncan & Humphreys, 1989): Distractors consisting of heterogeneously oriented Ls made visual search harder than did distractors of homogeneously oriented Ls. However, our results may not reflect the same phenomenon, because even in the uniform axes condition, the distractors differed in shape.

## EXPERIMENT 3

Experiment 2 showed that symmetry-defined visual search was carried out with an attentional set for axis orientation even when the task required no explicit decision about axis orientation. This outcome suggests that the observers explicitly detected vertical symmetry and horizontal symmetry separately, setting attention to each axis orientation. Therefore, the simple visual search tasks in Experiment 1, involving a search defined by symmetry–asymmetry with only one axis orientation in each search condition, were also considered to have been performed using an axis-based attentional set. Although those tasks involved no explicit requirement for processing axis orientation, the observers kept their attentional set for axis orientation and explicitly perceived axis orientation.

Experiment 3 was conducted to verify the explicit perception of axis orientation underlying the task in Experiment 1, which did not ask for an explicit decision about axis orientation. Experiment 3 required the observers to explicitly make a decision about axis orientation. There were two search conditions: Condition VH, in which the target was vertically symmetric and the distractors were horizontally symmetric, and Condition HV, in which the target was horizontally symmetric and the distractors were vertically symmetric. In these conditions, the visual search task could not be performed by making symmetry–asymmetry decisions irrespective of axis orientation, since both the target and the distractors were symmetric. If the task in Experiment 1 had been performed without an explicit perception of axis orientations, the search conditions in the present experiment should require additional processing to decide axis orientation. Consequently, longer RTs should be needed, in comparison with Experiment 1. However, if axis orientation was explicitly perceived in Experiment 1, the RTs in Experiment 3 should be equivalent to those in Experiment 1, and our supposition that attentional set for axis orientation was also used in Experiment 1 would be proved.

### Method

**Observers**. Twelve undergraduate and graduate students (including one of the authors) participated. All of them had participated in Experiment 1 on another day prior to this experiment. This procedure of observer matching enabled a direct comparison between the results of Experiments 1 and 3.[1]

**Design and Procedure**. All the observers performed both search conditions (VH and HV) in separate blocks. The target item was vertical (horizontal) symmetry, and the distractors were horizontal (vertical) symmetry for VH (HV). All the other procedures were identical to those in Experiment 1.

### Results

The mean RTs and mean error rates were analyzed along with the data from Experiment 1. Figure 4 shows the results.

**Reaction time**. As can be seen in Figure 4, serial search was evident for the VH and HV search conditions. We compared the RTs for all six of the search conditions for Experiments 1 and 3 and then conducted three-way repeated measures ANOVAs with the factors of search condition (VH, HV, VA, HA, AV, or AH), target presence, and display size. Significant main effects were found for all three factors [$F(5,55) = 16.78$, $p < .001$, $F(1,11) = 121.80$, $p < .001$, and $F(3,33) = 158.15$, $p < .001$, respectively]. All interactions were also significant: search condition × target presence [$F(5,55) = 13.17$, $p < .001$], search condition × display size [$F(15,165) = 16.53$, $p < .001$], target presence × display size [$F(3,33) = 21.76$, $p < .001$], and search condition × target presence × display size [$F(15,165) = 2.42$, $p < .01$].

Post hoc tests (Tukey's HSD, $\alpha = .05$) indicated that the mean RT for HA was significantly longer than the mean RTs for all five of the other conditions and that responses for the AV and HV conditions were significantly faster than those for the AH condition. In summary, the AV and HV searches were the fastest, HA was the slowest, and the other three (AH, VH, and VA) were intermediate. This tendency was common for both target-present and target-absent trials. The search conditions VH and HV, requiring explicit decisions of axis orientation, did not have longer RTs. Their search functions were virtually identical to those of search conditions that matched in distractors; VH was analogous to AH, and HV was analogous to AV. The mean slopes for VH were 100.9 msec/item (target present) and 151.3 msec/item (absent) and for HV, 57.4 and 78.6 msec/item, respectively. These values were comparable to the corresponding slopes for AH and AV (see the Experiment 1 results).

**Error rate**. The error rate data were analyzed in the same way as the RT data. There was not a significant main effect of search condition, according to the three-way re-

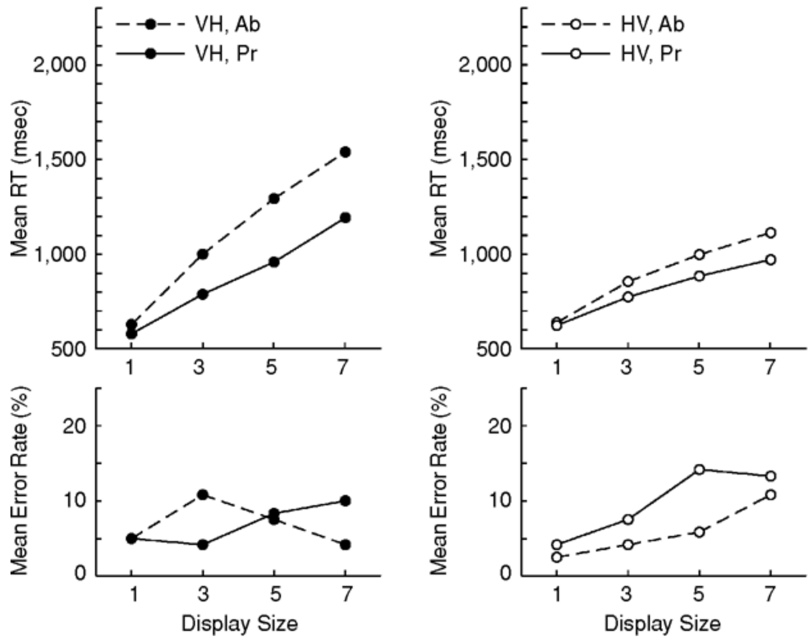


**Figure 4. Results of Experiment 3. Pr, target present; Ab, target absent. The condition VH (HV) indicates vertical (horizontal) symmetry target and horizontal (vertical) symmetry distractors. Note that the search functions for VH and HV were comparable to those for AH and AV, respectively, in Experiment 1 (see Figure 2).**

peated measures ANOVA. Thus, there was no evidence of a speed–accuracy trade-off.

### Discussion

We found no evidence that Experiment 3 required additional processing time for deciding axis orientation, in comparison with Experiment 1, which required only the detection of symmetry presence, irrespective of axis orientation. The search functions in Experiment 3 were nearly equivalent to those in Experiment 1 when distractor attribute was shared. Consequently, we suggest that VH (HV) and AH (AV) required the same processing of the distractors. The present results suggest that the observers did not detect symmetry in general, but vertical symmetry in AV and horizontal symmetry in AH, even though they had no requirement to explicitly process axis orientations.

Search functions for VH were similar to those not only for AH, but also for VA. Hence, VH search might be interpreted as a result of serial decisions of asymmetry per se or vertical symmetry absence, as well as of horizontal symmetry presence, of the distractors. We could not say that asymmetry per se was detected, as was discussed regarding Experiment 1. Thus, VH searches could have been based on decisions about the presence of horizontal symmetry, the absence of vertical symmetry, or both.

## GENERAL DISCUSSION

The observers performed all of our symmetry-defined visual search tasks, using serial scanning with selective spatial attention, replicating Olivers and van der Helm's (1998) findings and extending them to horizontal symmetry (Experiment 1) and axis-orientation-defined search (Experiment 3). Boutsen and Marendaz (2001) also obtained serial axis-orientation-defined search with more simple stimuli. These findings seem consistent with the feature integration theory of attention (Treisman & Gelade, 1980). The symmetric items used in our and Olivers and van der Helm's experiments were assemblies of symmetrically distributed visual elements; polygons which consisted of luminance-defined oriented edges, for example. Therefore, the symmetry of the items could be interpreted as a within-dimension conjunction of local visual features, not as a single feature that pops out. This does not necessarily mean that symmetry perception requires attentional serial scanning of local features. Although several researchers have found within-pattern serial processing of local elements in a symmetry–asymmetry judgment task (Huang & Pashler, 2002; Morales & Pashler, 1999), their asymmetric patterns contained few asymmetric elements and might be almost symmetric at a glance. To be judged asymmetric, such stimuli might require serial matching of elements. Since 8 of 12 apexes of our asymmetric patterns were asymmetrically located (Figure 1B), our present results suggest holistic processing of symmetry, rather than within-pattern scanning (symmetric items required shorter times to be processed than did asymmetric items). Baylis and Driver (2001) also have shown parallel processing for the perception of symmetry within single visual objects (no effect of the number of elements on RTs).

We also showed that the search efficiencies were systematically dependent on what kind of attribute was to be detected. Our observers performed visual search tasks involving separately detecting vertical or horizontal symmetry, rather than symmetry in general or asymmetry per se, even when there was no need to explicitly judge axis orientations. Furthermore, the attentional set for axis orientation enhanced the detection of symmetry for the attended alternative vertical or horizontal axes. For these reasons, we conclude that symmetry-defined visual search is fundamentally determined by an attentional set for axis orientation.

Given these results, the hypothesized mechanism of symmetry perception in the human visual system seems to be strongly modulated by some processes concerned with axis orientation. Since the mixture of axis orientations slowed down visual search RTs (Experiment 2), the visual system may be poorly suited for detecting the abstract attributes of symmetry, irrespective of axis orientation, by directing spatial selective attention only to location. However, many studies of symmetry perception explicitly or implicitly adopt the supposition that the mechanism of symmetry perception is versatile for axis orientation (e.g., Barlow & Reeves, 1979). If the processing of axis orientation is essential for symmetry perception, an attentional set for axis orientation must play an important role. Such attentional modulation of the mechanism of symmetry perception for the most likely axis orientation may contribute to economical perception of symmetry that has a potentially large range of axis orientations and may provide a means to make a single mechanism available for any given axis orientations.

It is still true, however, that briefly presented symmetry about an axis of any random orientation can be readily perceived, as many studies have demonstrated. At least one point should be examined: whether an attentional set for axis orientation, as we suggested, disrupts perception of symmetry across unattended axes or interferes only relatively. Another area of concern is symmetry with multiple axes, which is known to be relatively salient, in comparison with bilateral symmetry with only one axis (Palmer & Hemenway, 1978; Wagemans, Van Gool, & d'Ydewalle, 1991). Imagine dumbbells (two axes) or a star shape with five peaks (five axes), for example. The possible involvement of an attentional set for axis orientation in such kinds of symmetry is unclear.

Using single pattern stimuli, instead of multiple patterns stimuli such as our visual search array, Pashler (1990) examined the possibility that observers can "voluntarily set an internal coordinate frame" that facilitates the detection of symmetry about a specific axis. The hypothesized internal setting was tested by estimating the effect of a cue that informed observers of axis orientation in advance of the presentation of a dot pattern stimulus. Since the cue facilitated the detection of symmetry about the cued axis, the involvement of some internal preparation for the cued axis was suggested. However, an important and interesting point of the study might be that such internal preparation can be explained not only by an attentional set that contributes only to symmetry perception, but also by a general frame of reference that is equally responsible for object recognition. His Experiment 5 suggested that the preparation for a particular axis of symmetry facilitated the identification of letters that were aligned with that axis. This issue should be studied in further experiments including visual search paradigms.

If symmetry perception involves an attentional set for axis orientation, the well-known superiority of vertical symmetry over other axes seemingly is caused by a strategic biasing of the attentional set toward the vertical axis at the expense of other axes. Wenderoth (1994) demonstrated that the superiority of vertical symmetry was at least partly dependent on the subject's strategy. However, our results clearly showed that visual search was easier with vertical symmetry than with horizontal symmetry even when only one axis orientation appeared. Pashler (1990) also reported that consistently better performance was recorded for vertical symmetry than for other symmetries, despite cuing of axis orientations. Therefore, the superiority of vertical symmetry cannot be attributed fully to observers' strategic bias for the vertical axis. The mechanism of symmetry perception has a built-in preference for the vertical axis, which is frequent and familiar in natural scenes.

Overall, we suggest that two types of attentional processes are fundamentally involved in symmetry-defined visual search: visual selective attention to location and attentional set for axis orientation. The human ability to detect symmetry seems to be strictly limited to an attended location and is highly dependent on the attended axis orientation. The presence of symmetry per se does not attract visual attention, as is evident in the findings for a serial search process. Accordingly, it seems plausible that the visual system does not detect symmetry preattentively as a clue to the possible existence of any object but, instead, detects symmetry after attentional selection, in order to obtain detailed information about an attended object. Quinlan and Humphreys (1993), for example, suggested that the axis orientation of symmetry played an important role in the recognition of two-dimensional shapes. Further investigations should be done to confirm how visual symmetry is processed and utilized in visual recognition.

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## NOTE

1. To evaluate any effect of order, such as that from practice, we compared the mean RTs for the first half of the trials with those for the latter half of the trials for each search conditions in Experiments 1 and 3. We did not find significant differences between the halves for any search conditions, except for AV, that suggested a practice effect. The effect in AV was relatively small, and the search functions of both halves for AV did not significantly differ from those for HV (see the Discussion section).

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