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Research Report

SPATIAL ATTENTION IN VISUAL SEARCH FOR FEATURES AND FEATURE CONJUNCTIONS

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Abstract—*Spatial attention was measured in visual search tasks using a spatial probe. Both speed and accuracy measures showed that in a conjunction task, spatial attention was allocated to locations according to the presence of target features. Also, contrary to some predictions, spatial attention was used when a clearly distinguishable feature defined the target. The results raise questions about any account that assumes separate mechanisms for feature and conjunction search. The probe method demonstrated here allows a very direct measurement of attentional allocation, and may uncover aspects of selection not revealed by visual search.*

The visual system cannot simultaneously process all the information it receives. Many studies have focused on how one portion of the visual input is selected. They generally conclude that spatial attention—selecting visual information by location—is vital for detecting a target among distractors that share the target's basic features (Cave & Wolfe, 1990; Koch & Ullman, 1985; Nissen, 1985; Treisman & Gelade, 1980). On the one hand, feature integration theory (Treisman & Gelade, 1980; Treisman & Gormican, 1988) predicts that a target can be detected without attention if it differs from the distractors by some highly discriminable feature (feature target), but that search for a target defined by a combination of features (conjunction target) requires attention to the target's location. On the other hand, researchers have also suggested that a highly distinctive, popping-out feature target can call attention to itself, implying that spatial attention can automatically be allocated to both conjunction targets and feature targets (e.g., Hoffman, Nelson, & Houck, 1983; Treisman, 1988). However, few studies have measured spatial attention directly in a complex visual search array. Two experiments described here used response times (RTs; Experiment 1) or accuracy (Experiment 2) in detection of a spatial probe (Hoffman et al., 1983; LaBerge, 1983; Luck, Fan, & Hillyard, 1993; Sagi & Julesz, 1986; Tsal & Lavie, 1993). They explored the factors determining where attention is allocated in visual search, and how spatial selection's role varies in different search tasks.

EXPERIMENT 1: RT PROBES

Experiment 1 measured RTs to a probe in visual search tasks (Fig. 1). In conjunction search, 72 subjects searched for one of four elements as a target: a red square, red circle, green square, or green circle (the primary task). Each trial included the other three element types as distractors. Distractors were classified as "same color," "same shape," or "neither" based on the properties they shared with the target. Subjects held their response to the search until prompted by the computer. They were instructed that speed was unimportant, and that they should concentrate on accuracy.

On 25% of the trials, the search display was followed by a probe (small black dot) appearing in a position formerly occupied by either the target or a distractor. The probe appeared at each of the seven element locations equally often, regardless of the target's location. In response to the probe, subjects pressed a button as quickly as possible. For each subject, the probe appeared either 60, 105, or 135 ms after onset of the search display, because we could not predict in advance exactly when the probe should appear so that it would receive the full effect of spatial attention. This variation in stimulus onset asynchrony (SOA) also allowed us to investigate attentional changes over time. If subjects missed the probe and did not press the space bar within 1,400 ms, or they pressed it when no probe appeared, they heard an error sound. Likewise, in the primary task, when subjects responded incorrectly to the question about the target's presence, they heard a different error sound.

In feature search, 18 subjects searched for a feature target: a red circle among red squares or a red square among red circles. Most procedures were the same as in the conjunction condition, except that the search display time was shorter (15 ms) and SOA (30, 60, and 90 ms) varied for each subject. There were 1,176 trials in both conditions.

The probe RT reflects the degree to which spatial attention was allocated to the probed location during the visual search (Cave, 1995). In conjunction search, the responses to probes at the target location, and also to probes at the locations containing a distractor with the target color or the target shape, were generally faster than responses to probes at locations with neither target feature (see Fig. 2). Analyses of variance (ANOVAs) on the mean RTs for the four element types showed significant main effects of element type in all three SOA conditions. The exact pattern of RT varied according to SOA. As shown in Figure 2 (left panel), early in visual search (60-ms SOA), the target and same-color locations were activated (see, e.g., Theeuwes, 1991, 1992). With a 105-ms SOA, RTs for the target location were significantly faster than those for same-shape or "neither" locations. With a 135-ms SOA, the same-shape locations were significantly faster than "neither" locations, although target and same-color locations were almost as fast.

The ANOVAs on the mean RTs for the four distances between a target and a probe showed a significant effect only with the 105-ms SOA (Fig. 2, middle panel). Post hoc analysis showed that RTs to a probe at the target position were significantly faster than at the neighboring positions.

When a target was absent, there were no significant differences among mean RTs to probes at the three types of distrac-

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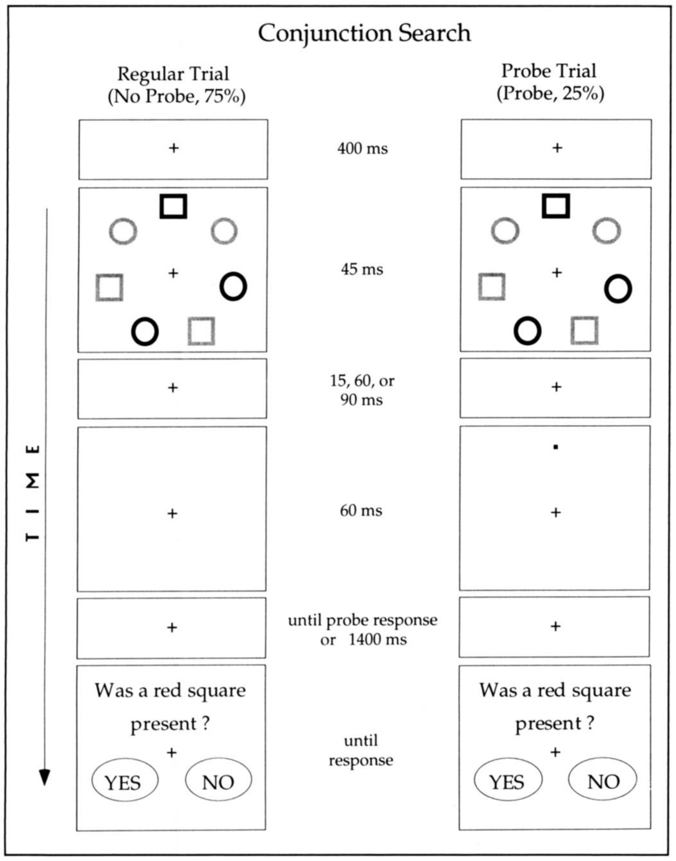

Fig. 1. Sequence of displays for the conjunction search condition in Experiment 1. Each search stimulus consisted of seven colored shapes presented against a white background. The shapes were equally spaced on an imaginary circle around the fixation cross. Red shapes are shown here as black, and green shapes as gray. With a viewing distance of 40 cm, the circle spanned 15.8° visual angle. Each shape approximated 2.9° visual angle. At the beginning of each trial, a fixation cross appeared for 400 ms, and the primary display then appeared for 45 ms. In 25% of the trials (probe trials), a probe appeared after a brief interval for 60 ms in the center of one of the locations previously occupied by an element. After the subject responded to the probe or after a fixed interval had passed with no response, a question appeared, asking if a target was present. For the feature search condition, the primary stimulus array contained distractors of only one type, and the primary display time and stimulus onset asynchronies were shorter.

tor locations in 60-ms and 135-ms SOA conditions, whereas RTs to probes at same-color and same-shape locations were significantly shorter than RTs at "neither" locations at the 105-ms SOA (Fig. 2, right panel). In both target-present and target-absent trials, the 105-ms probes appear to have been the best timed to reflect spatial attention effects in this particular task.

For conjunction searches, correct response rates were above 95% in the primary task and above 98% in the probe task in all three SOA conditions. RTs more than 3.5 *SD* from the mean were trimmed iteratively. They were less than 3% of all observations.

In feature search, RTs from each target condition were analyzed separately. With circle targets, Tukey compromise post hoc analyses with $\alpha = .05$ showed that the RTs were faster at the target position than at any other position, indicating that spatial attention was allocated to circle targets among squares. There was neither a main effect of SOA nor an interaction between SOA and distance (Fig. 3, left panel). With square targets, however, RTs for target and distractor locations did not differ significantly (Fig. 3, middle panel), suggesting that subjects either did not use attention when the target was a square or attended to the entire configuration. Because of the differing RT patterns, an ANOVA was performed on the error rates in the primary task to examine which target was more difficult to detect. When the target was a circle, 95.9% of primary-task responses were correct; when it was a square, 98.6% were correct. The difference was significant. Moreover, there was also a significant interaction between target type (circle vs. square) and probe (present vs. absent). Although the difference in error rates between circle targets and square targets was small in the probe-absent condition (99.1% and 99.6% correct, respectively), this difference was large when a probe was present (92.7% for circle targets and 97.5% for square targets).

Attention may also have been allocated to the square targets, however. Its effect might have been missed if the saliency of the square target drew attention to its location so quickly that it was deallocated before it could affect detection of the probe. This conjecture was tested with 15 new subjects, using the same procedures as described. There was only one target condition: Subjects searched for a square among circles. Also, only two SOAs (0 ms, 15 ms), both shorter than those in the previous feature search tasks, were used. Mean RTs at the target location were not significantly faster than RTs at distractor locations for either SOA (Fig. 3, right panel).

In the feature searches, more than 99% of probe responses were correct. With square targets and the fastest SOAs, correct responses were above 98% in the primary task. Trimming removed about 3% of the feature search trials.

Contrary to the results from location cuing experiments (Downing & Pinker, 1985; Luck et al., 1993; Rizzolatti, Riggio, Dascola, & Umiltá, 1987; Zimba & Hughes, 1987), these results show no systematic attentional changes with distance from a target. Instead, each location with a target feature received some attentional facilitation. With distractors present, spatial attention is apparently allocated more specifically, to only those locations with features known to belong to the target.

EXPERIMENT 2: ACCURACY PROBES

In Experiment 2, subjects were presented with the same primary search display as in Experiment 1 except that the display contained eight equally spaced stimuli placed on an imaginary circle subtending 12.7° visual angle in diameter. Each stimulus subtended a visual angle of 2.3°. Twenty-four subjects searched for one of four conjunction targets (a red square, red circle, green square, or green circle), and another 24 subjects searched for a feature target (a red circle among red squares or a red square among red circles).

Each trial consisted of the following sequence: First, a fixation cross appeared at the center of the screen for 1 s, and the primary (search) display appeared for 60 ms. Following a ran-

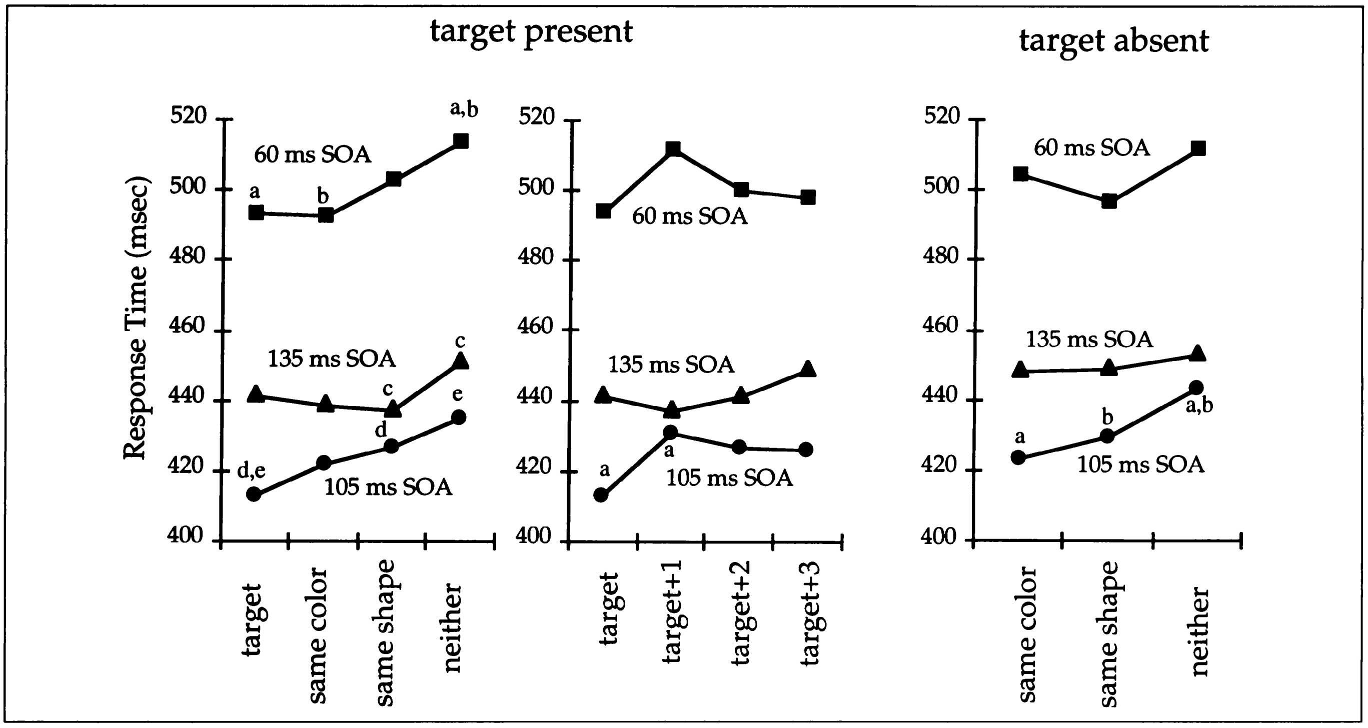

Fig. 2. Results from conjunction search in Experiment 1. The left panel shows response times (RTs) to probes at locations occupied by the target and the three distractor types with target present. The middle panel shows the same RTs organized by distance of the probe from the target. Locations next to a target are labeled "target + 1," those two positions away are labeled "target + 2," etc. The right panel shows RTs to a probe at the location of each distractor type with target absent. RTs labeled with the same letter differed significantly from each other in a Tukey compromise post hoc analysis (α = .05), which compared every pair of conditions. SOA = stimulus onset asynchrony.

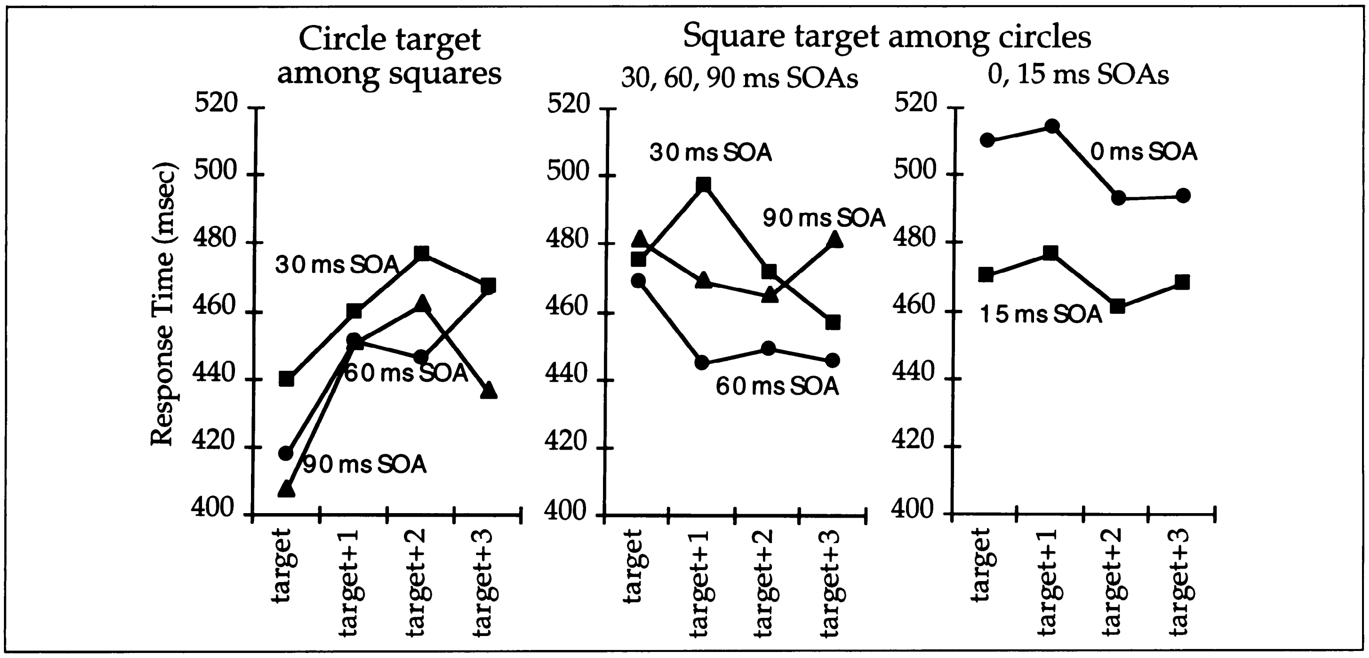

Fig. 3. Feature search in Experiment 1. The three graphs all show mean response times organized by distance from the target. The left panel shows data for search for a circle among squares, and the center and right panels show response times for search for a square among circles. SOA = stimulus onset asynchrony.

domly selected SOA of 75, 105, or 135 ms after the search display onset, a circular array of eight randomly selected black letters (all consonants) appeared, each in the center of the location previously occupied by a search element. The letters were visible for 60 ms. Each letter subtended a visual angle of 0.8° vertically and 0.6° horizontally. We expected allocation of attention at a specific location to facilitate detection of a letter appearing at that location (Tsal & Lavie, 1993). For the primary task, subjects reported whether there was a target or not by pressing a "yes" or "no" button with one of two fingers of the nondominant hand. The importance of a correct and speedy response in the primary task was emphasized. After this response, a display containing all possible letters appeared. Using a mouse, subjects pointed to letters they had seen in the probe array. They were instructed that accuracy was important and that speed did not matter. If subjects responded incorrectly in the primary search task, they heard an error sound. Likewise, if they reported incorrect letters or reported no letters, they heard a different error sound. Each subject performed 288 trials.

Overall, the subjects produced more errors in both the primary and the probe tasks than in Experiment 1, perhaps because the primary stimulus array contained eight items rather than seven, and the probe task was to identify letters rather than simply to detect a dot. Also, the letter probes might have masked the primary stimulus more. In the conjunction condition, subjects responded incorrectly to the target in 30% of the trials and reported incorrect probe letters in 26% of the trials. In feature search, subjects produced incorrect responses in the primary task on 11% of the trials and incorrect responses in the probe task on 21% of the trials. On the average, 1.86 and 1.85 probe letters per trial were correctly reported in conjunction and feature search conditions, respectively.

The mean proportions of correctly reported probe letters in each condition from trials with correct responses in both primary and probe tasks were subjected to ANOVAs. The results generally confirmed the results from Experiment 1. As shown in Figure 4, in both conditions, subjects correctly reported the letters preceded by the target more frequently than those preceded by a distractor. In the conjunction condition, contrasts showed that probes were detected more accurately at the target position than at locations with any of the three distractor types. In both the target-present and the target-absent conditions, letter probes at same-shape locations were reported correctly significantly more often than those at neither locations, and probes at same-color locations were reported correctly more often than those at either same-shape or neither locations. Unlike the RT results, the accuracy results show no influence of SOA. Moreover, Experiment 2 showed much stronger facilitation at the target location than Experiment 1, and also produced relatively strong activation at the locations with same color in all three SOA conditions.

More surprisingly, in feature search (Fig. 4, right panel), subjects showed a strong facilitation at square target locations

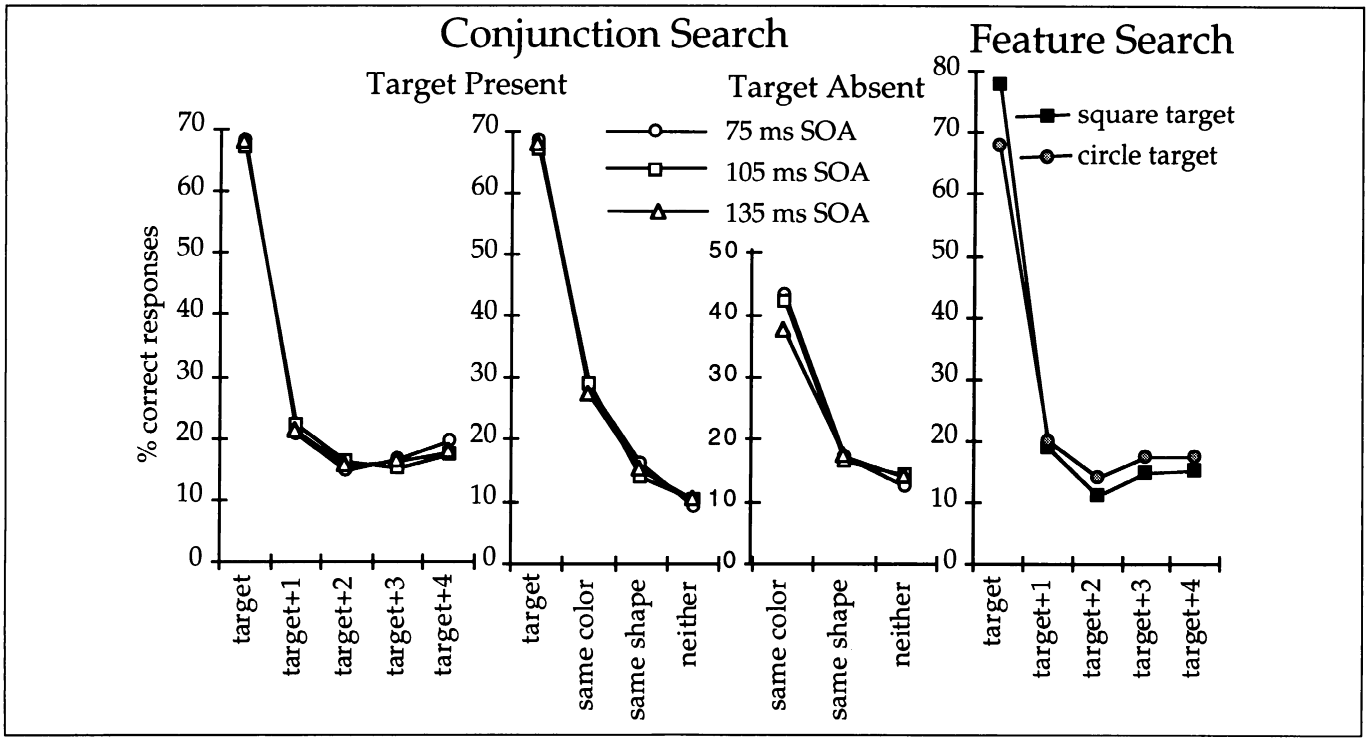

Fig. 4. Percentage of correct responses to probe letters in Experiment 2. The two left panels show data for target-present conjunction search, organized by distance from the target (far left) and by the target and the three distractor types (center left). The center right panel shows data for target-absent conjunction search, organized by the three distractor types. The far right panel shows data for target-present feature search, organized by distance from the target. In feature search, results from the three stimulus onset asynchronies (SOAs) are combined because subjects' response patterns for them were almost identical.

as well as circle target locations in all three SOAs. Once again, there were no systematic attentional changes with distance from a target. Instead of there being an attentional gradient (e.g., LaBerge & Brown, 1989), only the location with the target feature received attentional facilitation.

DISCUSSION

In Experiments 1 and 2, we measured spatial attention in visual search tasks using a probe technique. In conjunction search, the results suggest feature-driven selection, in which attention is allocated to locations containing either of the target features. Effects of attention were greatest for target locations, followed by distractor locations with the target color, and then by distractor locations with the target shape.

Feature search targets defined by shape also drew spatial attention to their locations. An additional feature search experiment with one, four, or seven items in each display produced search slopes of 0.25 ms/item for square targets and 3.98 ms/item for circle targets. These slopes are well below the 6 to 10 ms/item normally taken to indicate serial search (e.g., Duncan & Humphreys, 1989; Treisman & Souther, 1985; Wolfe & Pokorny, 1990). Thus, the probe results show that attention can be used in a very easy search that produces slopes generally considered to be parallel. Spatial selection must be more than just a facilitative mechanism for the most difficult searches, because it is used in at least some searches for clearly discriminable features. These results suggest that spatial selection is not limited to conjunction searches. Instead, a single spatial selection mechanism appears to work in conjunction and at least some feature searches.

These results also indicate a search asymmetry (Treisman & Gormican, 1988), with square targets requiring less attention for detection than circle targets. Perhaps the angles in the square targets served as a distinguishing feature. In fact, the RT probes showed no evidence of attention allocated to locations of square targets. There is a similar asymmetry in search slopes, with slopes for circle targets being significantly higher than those for square targets, $F(1, 34) = 6.5, p < .05$. However, probe letter accuracy clearly showed attentional allocation with both targets. Attention may have been more important to the primary task when letter probes were present. Because the letters were larger and appeared more frequently than the dot probes, they may have masked the primary stimuli more. Also, the letter identification task probably benefited more from attention than the dot detection task, which would explain the larger attentional effects in Experiment 2. Subjects may have been more likely to allocate attention for the primary task in Experiment 2 and then maintain it to help in identifying one of the target letters. This sustained attention may explain why the attentional pattern is so much more consistent across SOAs in Experiment 2 than in Experiment 1.

One might argue that attention is automatically allocated to every target after it is identified, and that the presence of spatial attention in feature search does not indicate a need for selection (e.g., Treisman, 1988). If that were true, however, then a spatial attention effect should have been found at the simple square target in Experiment 1 as well. The feature search slopes just described show that the square target is more easily detected than the circle. If every target received attention automatically, its location would certainly be selected. Because the attentional allocation was stronger for circle targets than for squares in Experiment 1, attention must have been serving a useful role in processing. It is not just an automatic response to a target.

The results presented here cannot determine how many locations were activated simultaneously. Locations with potential target features may be selected serially, as in the guided search model (Cave & Wolfe, 1990; Wolfe, Cave, & Franzel, 1989), or may all be selected simultaneously. The results also do not show whether spatial attention is an obligatory processing step in every visual task.

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