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The Contribution of Covert Attention to the Set-Size and Eccentricity Effects in Visual Search

Marisa Carrasco and Yaffa Yeshurun
New York University

To reexamine the role of covert attention in visual search, the authors directly manipulated attention by peripherally cueing the target location and analyzed its effects on the *set-size* and the *eccentricity* effects. Observers participated in feature and conjunction tasks. Experiment 1 used precues, and Experiment 2 used postcues in a yes–no task under valid-, invalid-, and neutral-cueing conditions. Experiments 3 and 4 used a 2-interval alternative forced-choice visual-search task under cued and neutral conditions. Precueing the target location improved performance in feature and conjunction searches; postcueing did not. For the cued targets, the eccentricity effect for features and conjunctions was diminished, suggesting that the attentional mechanism improves the quality of the sensory representation of the attended location. The conjunction set-size effect was reduced but not eliminated. This questions *serial-search* models that attribute a major role to covert attention in visual search.

Visual search is one of the leading paradigms in the study of visual perception and attention. In a typical visual-search experiment, observers have to decide whether or not a target is present in a visual array containing other nonrelevant items (distractors). For some stimuli, but not for all, reaction time (RT) increases as the number of distractors increases, a phenomenon known as the *set-size effect.* A large number of studies that attribute this effect to limited covert attentional processes have used the visual-search paradigm to investigate the nature of attention allocation. When performance is not affected by the number of distractors, it is assumed that the array is searched in parallel, preattentively, but a performance that deteriorates as set size increases is interpreted as indicating a covert attentional serial search (e.g., Treisman & Gelade, 1980; Treisman & Gormican, 1988; Wolfe, Cave, & Franzel, 1989). Surprisingly, the role of covert attention, that is, the focusing of attention on a stimulus or a location in the absence of an eye or head overt-orienting response, has seldom been examined directly in visual-search studies. In light of recent findings showing that the set-size effect is affected by sensory factors and does not necessarily reflect covert attentional shifts (Carrasco, Evert, Chang, & Katz, 1995; Carrasco & Frieder, 1997; Geisler & Chou, 1995; Verghese & Nakayama, 1994), we find it crucial to reexamine the role of covert attention. In this study, we directly manipulated attention by peripherally cueing the target location, to investigate its effects on both the set-size and the eccentricity effects in visual search.

Most of the models that have been developed to account for the set-size effect place attentional processes at the core of their interpretation. For instance, according to feature integration theory (FIT; e.g., Treisman, 1985, 1988; Treisman & Gelade, 1980), visual processing has two stages: an early preattentive stage, in which features are coded in parallel, and a later stage, in which attention is required to conjoin these features, serially, into complex objects. Thus, according to FIT, when the target differs from the distractors by a single feature (e.g., color—the observer searches for a red line among blue lines), a parallel search is performed. On the other hand, when the target differs in a conjunction of features (e.g., Color × Orientation—a red vertical line among red tilted lines and blue vertical lines), a successive shifting of attention is required, and performance decreases as set size increases.

The fact that many studies found a linear increment in RT as well as a 2:1 slope ratio for "absent" and "present" trials has been interpreted as evidence for a serial, self-terminating search (e.g., Treisman & Gelade, 1980; Treisman & Gormican, 1988; Treisman & Sato, 1990). The strict dichotomy between parallel feature searches and serial conjunction searches, however, has been challenged by findings in both feature (Bergen & Julesz, 1983a; Cheal & Lyon, 1992a; Pashler, 1987b; Quinlan & Humphreys, 1987; Treisman & Gormican, 1988) and conjunction (Egeth, Virzi, & Garbart, 1984; Nakayama & Silverman, 1986; Pashler, 1987a; Steinman, 1987; Ward & McClelland, 1989; Wolfe et al., 1989) searches.[1] In response, a revised version of FIT has been put forth, which states that the attentive mechanism operates

Marisa Carrasco and Yaffa Yeshurun, Department of Psychology, New York University.

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Correspondence concerning this article should be addressed to Marisa Carrasco, Department of Psychology, New York University, 6 Washington Place, New York, New York 10003-6634. Electronic mail may be sent to marisa@xp.psych.nyu.edu.

[1] Recently, it has been shown that illusory conjunctions (the incorrect combination of correctly perceived features), which according to FIT indicate a failure of focused attention (e.g., Treisman & Schmidt, 1982), are not affected by exposure duration (up to 1.5 s) or by diverting attention (Prinzmetal, Henderson, & Ivry, 1995).

along a continuum. In certain conditions, the distractors are clustered together and search becomes parallel within groups but serial between groups (Treisman & Gormican, 1988; see also Pashler, 1987a). An alternative account of search data is provided by the guided search model (GSM; e.g., Wolfe, 1994; Wolfe et al., 1989). This model suggests that a parallel process that provides information about simple features guides attention, so that only the items that have one of the relevant features of the target are examined, thus decreasing the number of elements that are searched serially in a second stage.

Another problem in the visual-search literature is that a serial search is not the only search pattern that can account for the linear functions obtained in many studies (e.g., Enns & Rensink, 1990a, 1990b; Treisman & Sato, 1990; Wolfe et al., 1989). Townsend (1972, 1990) claimed that linear functions can only indicate limitations in capacity and that both serial and parallel searches can be either of limited or unlimited capacity. For instance, a parallel search in which each additional item is processed at the same time, but in a lower rate, could also result in a linear function (e.g., Kinchla, 1992). Yet another interpretation emphasizes the degraded quality of the sensory impressions as producing a linear set-size effect. This "confusability" view attributes this effect to the increased risk of confusing the target with a distractor as the number of distractors increases (Kinchla, 1974; Kinchla, Chen, & Evert, 1995; Palmer, 1994; Palmer, Ames, & Lindsey, 1993). Furthermore, when using a wide range of set sizes, logarithmic and quadratic functions fit the data better than the linear function (Carrasco et al., 1995; Carrasco & Katz, 1992). The linear search is central to FIT, GSM, and other models of visual search, and the possibility that these functions resulted from a too narrow range of set sizes questions a basic tenet of these theories.

Most visual-search models attribute the set-size effect to covert attentional mechanisms. Yet, the set-size effect may be due, at least partially, to sensory factors, in particular to spatial resolution and lateral inhibition (Carrasco et al., 1995; Carrasco & Frieder, 1997). Most of these models overlook the physiological limitations on visual perception, such as when retinal eccentricity increases, spatial resolution decreases and position uncertainty and lateral inhibition increase (e.g., DeValois & DeValois, 1988). Moreover, by systematically controlling target location and analyzing search performance as a function of target eccentricity, Carrasco et al. found a strong eccentricity effect: Performance deteriorated as the target appeared on increasing field–retinal eccentricities, and the set-size effect became more pronounced as target eccentricity increased. Given that the probability of items appearing in peripheral regions increases for larger set sizes, Carrasco et al. suggested that the typical decrement in performance as set size increases may be due to spatial resolution factors rather than to covert attentional shifts.

To examine the role of spatial resolution in the eccentricity effect, Carrasco and Frieder (1997) used Virsu and Rovamo's (1979) "cortical magnification factor" (M-scaling). By enlarging the size of the peripheral stimuli, M-scaling attempts to equate the cortical representation of peripheral stimuli to that of the central stimuli (Virsu & Rovamo, 1979), mimicking the foveal resolution at the periphery. Indeed, M-scaling the stimuli eliminated the differences in sensitivity to spatial and temporal frequencies between retinal regions. In contrast, when differences between retinal regions exist after M-scaling, processing qualitative differences are assumed (Kitterle, 1986).

Carrasco and Frieder (1997) found that M-scaling the stimulus size eliminated the set-size effect for feature targets, decreased it for conjunction targets, and eliminated the eccentricity effect for both feature and conjunction targets. These findings demonstrate the crucial role of spatial resolution factors in visual-search tasks and support the claim that the set-size effect is due, at least partially, to spatial resolution variables, rather than to covert attentional processes. Furthermore, these findings confirm the importance of considering physiological constraints in any research of visual information processing. In the same vein, recent studies have emphasized the importance of equating low-level (sensory) factors before attributing performance to attention (e.g., Bergen & Julesz, 1983b; Carrasco, McLean, Katz, & Frieder, 1998; Geisler & Chou, 1995; Verghese & Nakayama, 1994; Palmer, 1994). Cheal and Lyon (1994) even suggested that visual search is a poor method for studying attentional effects.

The findings discussed thus far illustrate that the role of covert attention in visual search is no longer clear. In this study, we reexamined the role of covert attention in visual search. Several studies have shown that prior knowledge of the target's location improves performance. This improvement has been attributed to attention allocation to the cued location, which is considered either to affect postperceptual processes like decision integration (e.g., Kinchla, 1980; Palmer, 1994; Shaw, 1984; Sperling & Dosher, 1986) or to facilitate early stages of perceptual processing by enhancing the quality of the stimulus representation (e.g., Bashinski & Bacharach, 1980; Downing, 1988; Posner, Nissen, & Ogden, 1978; Posner, Snyder, & Davidson, 1980; Prinzmetal, Presti, & Posner, 1986; Tsal & Lavie, 1988). The latter is supported by the physiological findings, suggesting that spatial attention can narrow the receptive field and improve spatial resolution (Desimone, Wessinger, Thomas, & Schneider, 1990; Moran & Desimone, 1985; Olshausen, Anderson, & Van Essen, 1993).

The target's location has usually been specified by either a central cue presented in the center of the visual field (endogenous cue) or a peripheral cue presented in a location directly adjacent to the relevant location (exogenous cue). The findings that peripheral cues produce faster RTs than central cues and a greater difference between cued and not-cued locations have led to the conclusion that peripheral cues capture attention in an "automatic" manner, whereas central cues do so in a more controlled way[2] (Cheal & Lyon, 1991; Jonides, 1981; Müller & Findlay, 1988; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980;

[2] According to Cheal and Lyon (1991), performance with central cues is just as good as with peripheral cues provided a long enough interval is used for attention to focus on the cued location.

Posner & Cohen, 1984; Remington, Johnston, & Yantis, 1992; Yantis, 1996; but see Folk, Remington, & Johnston, 1992). For instance, peripheral irrelevant cues impair performance directed by relevant central cues (Müller & Rabbitt, 1989), and performance at peripheral cued locations is facilitated even when observers are instructed to ignore the peripheral noninformative cues (Jonides, 1981).

When observers know in advance the target location, they could allocate all their attentional resources to that location and no search may be needed. Thus, if the set-size effect is due to the growing number of items needed to be attentionally searched, performance for cued targets should not be affected by the number of items in the display. Indeed, precueing the target location has decreased the set-size effect in some (C. W. Eriksen & Hoffman, 1972a; Yantis & Jonides, 1984), but not other (Colegate, Hoffman, & Eriksen, 1973), studies. However, these studies did not conclusively answer how directing attention affects search performance for the following reasons: (a) They used a narrow range of set sizes (i.e., Colegate et al., 1973, 8 and 12; C. W. Eriksen & Hoffman, 1972a, 4, 8, and 12; Yantis & Jonides, 1984, 2 and 4), which may have affected the search pattern (e.g., Carrasco et al., 1995; Pashler, 1987a). (b) They did not investigate the way the deployment of attention is related to the target eccentricity in the display. Although the stimuli were presented on an imaginary circular display, controlling to some extent the eccentricity effect, this display resulted in a confounding of set size and density; the more items, the closer they are to each other (e.g., Carrasco et al., 1995; Colegate et al., 1973; Palmer et al., 1993). (c) Whereas Yantis and Jonides's task involved a detection search for a prespecified target, as is the case in a typical visual-search task, Eriksen and Hoffman's and Colegate et al.'s tasks required an identification of the item appearing at the precued location.

This study explored the effect of covert attention on the set-size and the eccentricity effects in visual search, using a wide range of set sizes (3–36) and manipulating target eccentricity. To achieve this goal, we combined the visual-search paradigm with a customary method used to directly manipulate attention. Observers searched for an orientation feature and for a Color × Orientation conjunction target. Attention was directly manipulated by a peripheral cue, which is considered to capture attention automatically to its location (e.g., Jonides, 1981; Posner, 1980). The cue was a small horizontal bar appearing above either the target location (valid cue) or a nontarget location (invalid cue). Experiments 1 (precue) and 2 (postcue) used the *yes–no* detection task. Experiments 3 and 4 explored whether similar results to those obtained with a precue in a yes–no task (Experiment 1) would be obtained with a precue in a two-interval alternative forced-choice (2AFC) visual-search task.

In light of current models of visual search (e.g., Duncan & Humphreys, 1989, 1992; Treisman, 1993; Treisman & Gormican, 1988; Wolfe, 1994; Wolfe et al., 1989), we expected the set-size effect to be eliminated when the target's location was cued because observers could devote all their attentional resources to the relevant location. In addition, on the basis of the idea that deploying attention to a specific location enhances perceptual processing at that location (e.g., Downing, 1988; Jonides, 1981; Posner, 1980; Tsal & Lavie, 1988), we expected the eccentricity effect to diminish in the cued trials.

Experiment 1

Experiment 1 assessed the role of covert attention in search performance by combining a typical visual-search task with a precueing technique. The target appeared in 66.66% of the total trials and differed from the distractors, either by a single orientation feature (feature task) or by a conjunction of Color × Orientation features (conjunction task). Two thirds of the total trials were *cued* trials: Prior to the display, onset attention was directed toward one location by a small horizontal bar that appeared above either the target location (*valid cue*, in 2/3 of the cued trials) or a nontarget location (*invalid cue*, in 1/3 of the cued trials).[3] The other third of the total trials consisted of *neutral* trials, in which a small circle was presented instead of the peripheral bar in the center of the display, indicating that the target was equally likely to appear in any of the locations.

Method

Observers. Eleven undergraduates from the New York University (NYU) student pool participated as observers. All had normal or corrected-to-normal vision and were unaware of the purpose of the study.

Apparatus. The stimuli were presented, using Vscope (Enns & Rensink, 1992), on a 15-in. (38.1-cm) monitor of a Macintosh Quadra 840AV computer, whose frame rate equals 13.4 ms.

Stimuli and design. The displays appeared on a black background and consisted of a red vertical line among either red tilted lines in the feature task or red tilted and blue vertical lines in the conjunction task. The vertical line subtended 0.5° Height × 0.1° Width of visual angle. The tilted line was identical to the vertical line, apart from being 135° (\). The brightness of both the blue and red (.155, .070 and .625, .340 in standard Comission Internationale de l'Ecleirage (CIE) color space, respectively) was set at 46% of maximum monitor brightness.[4] A small fixation dot was present in the center of the screen throughout the experiment. A plus (0.25° Height × 0.25° Width) or a minus (0.25° Width × 0.1° Height) sign served as the feedback and was presented in the center of the screen. On each trial the items were presented in one of eight possible set sizes (3, 6, 9, 12, 18, 24, 30, and 36) and were scattered randomly among 36 positions on a square grid composed of six rows by six columns. The square subtended a 12° × 12° of visual angle, and the items were centered at 1.4°, 3.2°, 4.2°, 5.2°, 5.8°, and 7.0° away from fixation point. A jitter of ±0.15° of visual angle was introduced to prevent a perfect alignment of the items in the display.

The target was present in 2/3 and absent in 1/3 of the total trials (Figure 1). A cue was shown on 2/3 of the total trials. On 2/3 of

[3] We included invalid trials so that observers could not base their performance on the fact that the presence of the cue necessarily indicated the presence of the target.

[4] Previous piloting work indicated that at this brightness level the discriminability of red and blue is the same (Carrasco & Katz, 1992).

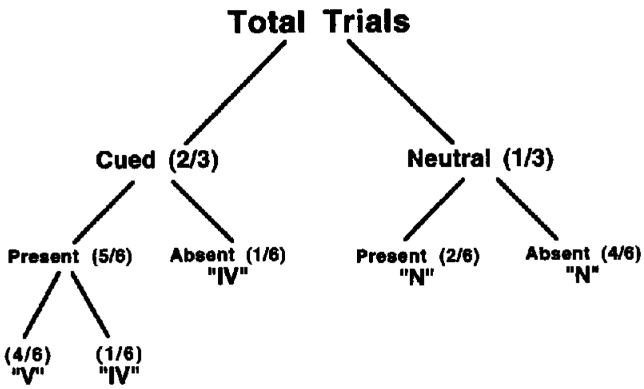

Figure 1. This diagram depicts the distribution of the total number of experimental trials in each experimental condition of Experiment 1. V = valid trials; IV = invalid trials; N = neutral trials.

these cued trials a bar appeared about 0.3° above the location of the target (valid cue), and on the other 1/3 cued trials it appeared above any of the other 35 locations (invalid cue). Half of the invalid cues preceded displays containing a target in any location other than the cued, and the other half preceded displays that did not contain a target. The cue was a green (.280, .595 in standard CIE color space) horizontal bar set at 46% of maximum monitor brightness, subtending 0.5° Width × 0.2° Height of visual angle. In the other 1/3 of the total trials (neutral trials), instead of the bar a green circle, whose diameter subtended 0.3° of visual angle, appeared in the center of the display. This circle indicated that if the target was present, it had equal probability of appearing at any location. On 1/3 of these neutral trials the circle preceded displays containing a target, and on the other 2/3 it preceded displays that did not contain a target. (We included more absent than present trials in the neutral condition so that the total distribution of trials would be 2:1, present to absent.)

Procedure. The observers were read instructions specifying the target, advising them to fixate on the fixation point throughout the experiment and asking them to indicate, as rapidly and accurately as possible, whether or not the target was present in the display. Each observer was then given 96 practice trials before each of the four experimental sessions. In two 1-hr sessions observers performed a feature task, and in the other two sessions they performed a conjunction task. Each session consisted of nine blocks of 96 trials, for a total of 3,456 experimental trials per observer. When the target was present it appeared at each of six eccentricities, for each of eight set sizes, under each of the three cueing conditions. The order of presentation of the experimental sessions was counterbalanced, and the order of the trials within a session was randomized. In each of the trials the bar or the circle appeared for 40 ms, and after an interstimulus interval (ISI) of 54 ms, the display was presented for 94 ms. Thus, eye movements could not take place while the display was present; it is estimated that 200–300 ms are needed for saccades to occur (Mayfrank, Kimmig, & Fischer, 1987). Observers responded by pressing a key on the computer keyboard with the index or middle finger of their dominant hand. Half the observers used their index finger for a "yes" response, and the other half used their middle finger. Immediately after observers responded, the appropriate feedback sign was presented for 1 s.

Results and Discussion

Present versus absent analysis. To evaluate the effect of the presence or absence of the target, a three-way within-observer analysis of variance (ANOVA; Target Type [present vs. absent] × Cue Type [invalid vs. neutral] × Set Size [3 to 36]) was performed on mean correct RTs and error rate. (Given that we compared performance for present and absent trials, this analysis did not include the valid cue type; there cannot be a match between cue and target location for absent trials.) As can be seen in Figure 2, absent took longer than present trials in both features, $F(1, 10) = 78.44$, $p < .0005$, and conjunctions, $F(1, 10) = 24.64$, $p < .001$; error rate did not differ significantly. Performance was impaired as a function of set size, for feature—errors, $F(7, 70) = 2.86$, $p < .05$, and conjunction—RT, $F(7, 70) = 27.98$, $p < .0001$, and errors, $F(7, 70) = 58.38$, $p < .0005$—searches. However, the least square slope estimates indicated that the conjunctions' absent to present slope ratio of 1.4:1 differed, $t(7) = 39.71$, $p < .0001$, from the 2:1 ratio considered to be indicative of a serial self-terminating search (e.g., Treisman & Sato, 1990; Wolfe et al., 1989).

There was a significant Cue Type × Target interaction for the feature's error rate: The cue type was only significant for the absent trials; neutral trials were faster, $F(1, 10) = 52.98$, $p < .0005$, and more accurate, $F(1, 10) = 26.58$, $p < .0005$, than invalid trials. That is, when the probability of absent targets was lower (invalid trials: 1/9; neutral trials: 2/9) RT and errors increased. Although this could indicate that observers' criterion was not constant across cueing conditions, note that this was not the case in the present feature task or in the conjunction task. Moreover, observers had only advanced knowledge that in cued trials the bar would indicate "most of the time" where the target would appear; they had no knowledge of the distribution of cued versus neutral trials or present versus absent trials. Although observers could have estimated the distribution of the trials, some comparisons illustrate that this was not the case for either features or conjunctions. For instance, in the neutral trials, observers should have had more misses than false alarms, because the probability was lower for the present than for the absent target. In the present trials, observers should have detected the target faster and/or more accurately in the invalid cued than in the neutral trials, because the probability of the target being present was higher for the cued than for the neutral trials and observers did not know in advance if the cue was valid or invalid.

Target present analysis. The more important analyses of this experiment regard the present targets because their main goal was to evaluate the effect(s) of precueing target location on the set-size and eccentricity effects. A three-way within-observer ANOVA (Cue Type [valid, invalid, neutral] × Eccentricity [1.4° to 7°] × Set Size [3 to 36]) was performed on mean correct RTs and error rate of the present trials. A separate analysis was performed for feature and conjunction searches (Table 1).

As was expected, for both search types, targets cued by a valid cue were detected faster and more accurately than

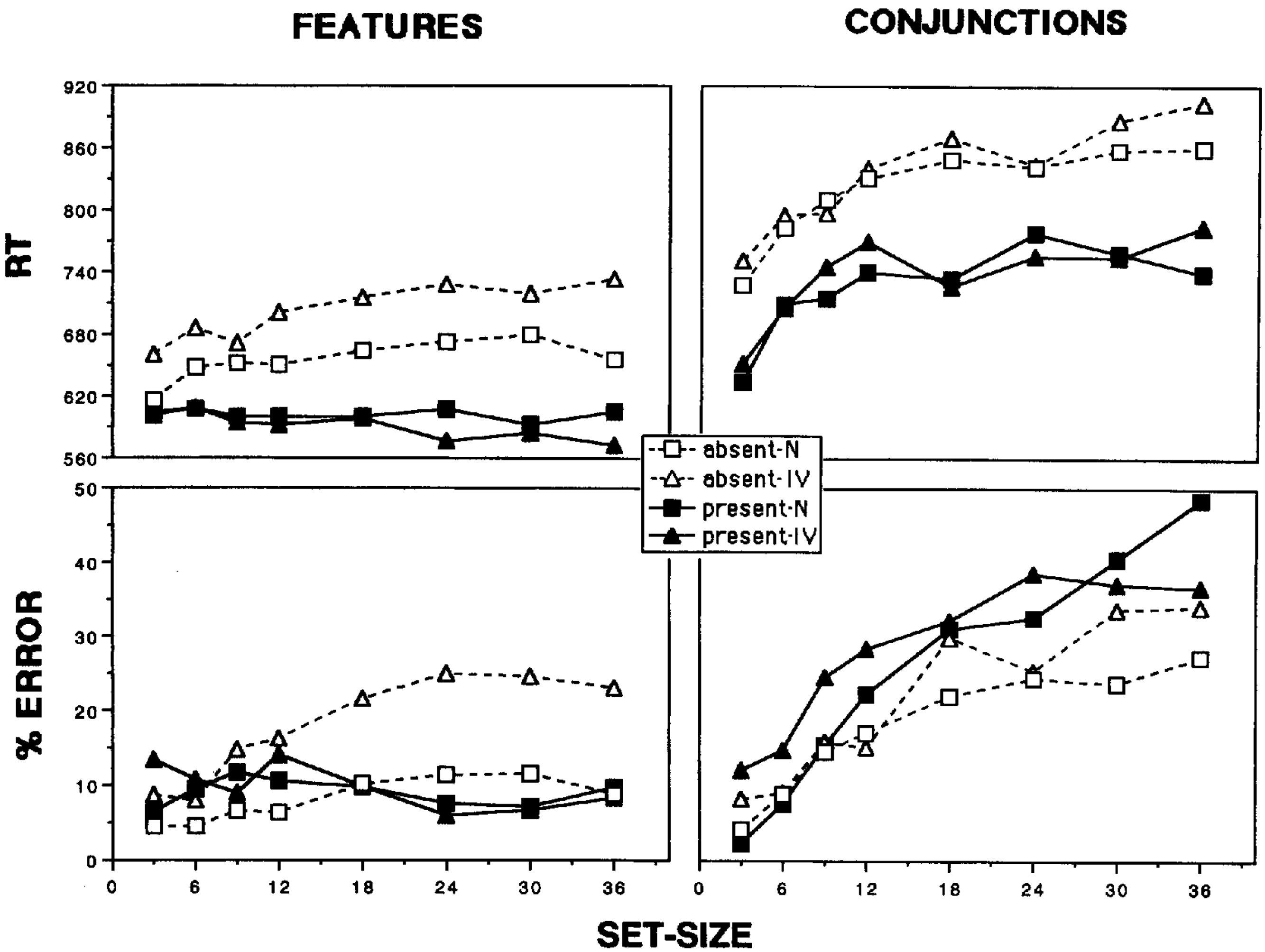

Figure 2. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of the presence or absence of the target and set size under the different cueing conditions (Experiment 1). N = neutral trials; IV = invalid trials.

targets cued by neutral or by invalid cues (Figure 3). This improvement in performance for the valid-cued stimuli has been found previously by various studies and is often interpreted as reflecting a perceptual advantage because of advance allocation of processing resources to the target location (e.g., Bashinski & Bacharach, 1980; Müller & Findlay, 1987; Posner et al., 1980; Van der Heijden & Earland, 1973). However, this main cueing effect was due to only a significant benefit in RT and accuracy for the valid condition compared with the other conditions. The lack of a significant difference between the invalid and the neutral conditions may be due to the fact that in both cases the target could have appeared in a neighboring location to, or a number of locations away from, either the bar that cued a location or the circle that announced a neutral trial. Thus, the cost of the invalid cueing resulted in similar performance to that of the neutral condition, in which observers were not induced to allocate resources to a specific location.

According to RT and error rate, the set-size effect was significant only when the target was defined by a conjunction of features. This finding is in agreement with several previous studies (e.g., Treisman, 1982; Treisman & Gelade, 1980; Treisman & Paterson, 1984). The eccentricity effect was significant in both search types for both RT and error rate. This is in agreement with previous findings in our lab (Carrasco et al., 1995, 1998; Carrasco & Frieder, 1997). The highest conjunction error rate, which occurred at the largest set sizes, resulted from the farthest target eccentricities (Figure 3). A linear regression revealed that whereas there was a slope of 0.28% error per item when the target appeared at 1.4°, the slope was 0.83% error per item when it appeared at 7.0° of eccentricity. Furthermore, the Set-Size × Target Eccentricity interaction for both RT and error rate in conjunction search, and for error rate in feature search, indicated that the set-size effect was more pronounced at farther eccentricities. Such an interaction supports the notion that the set-size effect is inflated by the eccentricity effect and questions the assertion that the set-size effect necessarily

Table 1
Experiment 1 Analysis of Variance Results

Factor	*df*	Reaction time *F*	Reaction time *p*	Error *F*	Error *p*
		Feature search			
Cue	2, 10	120.61	.0005	17.06	.0005
Eccentricity (Ecc)	5, 50	23.90	.0005	7.28	.0005
Set size (SS)	7, 70	<1	*ns*	1.43	*ns*
Cue × Ecc	10, 100	7.54	.0005	2.49	.05
Cue × SS	14, 140	2.05	.02	<1	*ns*
Ecc × SS	35, 350	1.03	*ns*	1.55	.03
Cue × Ecc × SS	70, 700	<1	*ns*	1.06	*ns*
		Conjunction search			
Cue	2, 10	45.10	.0005	37.08	.0005
Eccentricity	5, 50	51.84	.0005	22.11	.0005
Set size	7, 70	19.16	.0005	25.37	.0005
Cue × Ecc	10, 100	4.21	.0005	8.94	.0005
Cue × SS	14, 140	1.22	*ns*	4.88	.0005
Ecc × SS	35, 350	1.67	.02	2.83	.0005
Cue × Ecc × SS	70, 700	<1	*ns*	1.25	*ns*

reflects covert attention (Carrasco et al., 1995; Carrasco & Frieder, 1997).

The interaction of cue and set size. Central to this study was the manner in which directing attention interacts with the set-size effect. There was no significant RT Cue Type × Set Size interaction (Figure 4): The magnitude of the set-size effect was constant for the three cueing conditions; the slope was 3 ms per item for all conjunction conditions and fluctuated from −0.9 to 0.9 for the feature conditions. According to the ANOVA, only in the conjunction error rate data did the magnitude of the set-size effect decrease for the valid cue. Furthermore, for the three conjunction cueing conditions the RT and error rate slopes were significantly different from zero ($p < .05$). These slopes are shallower than those obtained in studies that have used fewer and a more limited range of set sizes (e.g., Chmiel, 1989; Donnelly, Humphreys, & Riddoch, 1991; Treisman, 1988; Treisman & Sato, 1990). However, as we considered a more narrow range of set sizes the slopes became steeper (Figure 5). In addition, the RT functions were best described by the logarithmic fit. For the whole range of set sizes the adjusted R^2 for the logarithmic fit (valid, 0.99; neutral, 0.88) were higher than for the linear fit (valid, 0.87; neutral, 0.60). The finding that when a large number and range of set sizes are used, nonmonotonic RT functions emerge, illustrates the inadequacy of using a linear function to characterize the search pattern; the milliseconds per item linear slope would be meaningless. In any case, analysis of this narrower range of items revealed that, as was the case for the whole range of set sizes, the valid cue improved performance but did not eliminate the set-size effect. Again, all slopes were significantly different from zero ($p < .05$).

Our results do not agree with the common hypothesis regarding the nature of the set-size effect (e.g., Treisman, 1993; Treisman & Gormican, 1988; Wolfe, 1994; Wolfe et al., 1989). If the set-size effect was due to the growth in number of items to be searched, then one should expect the

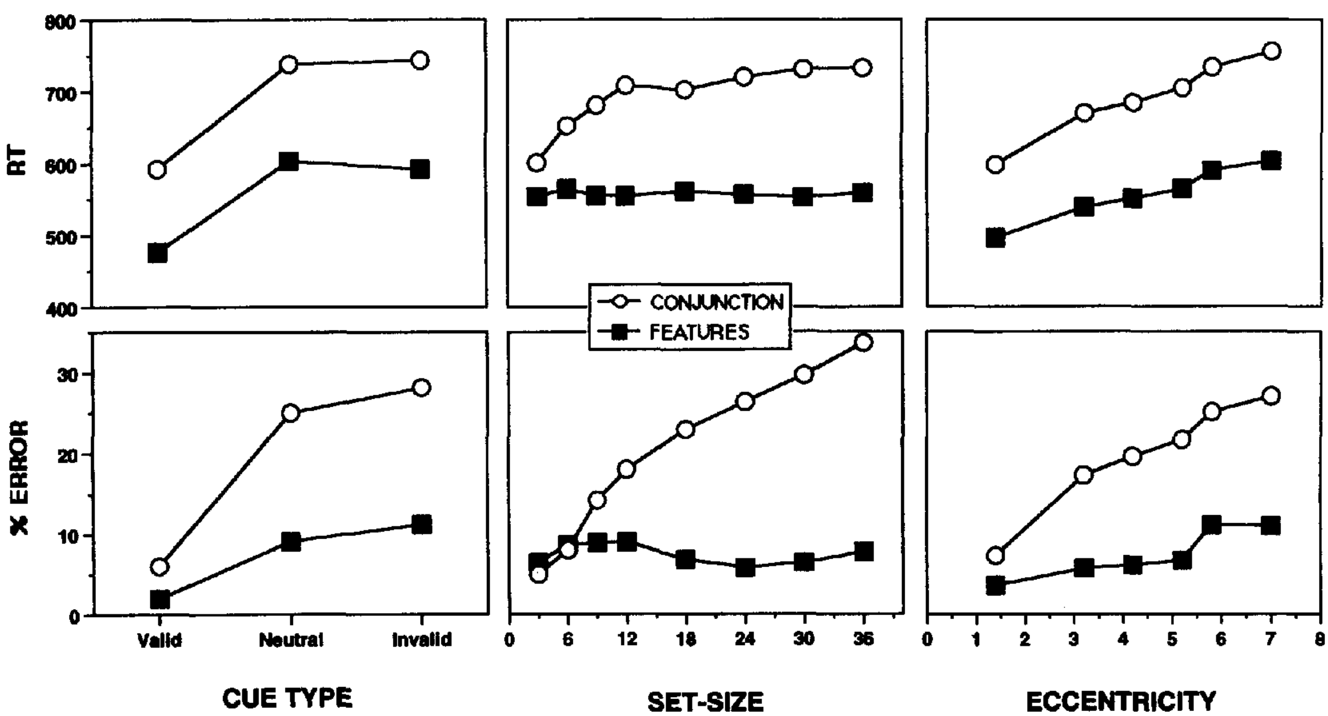

Figure 3. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of cue type, set size, and target eccentricity (Experiment 1).

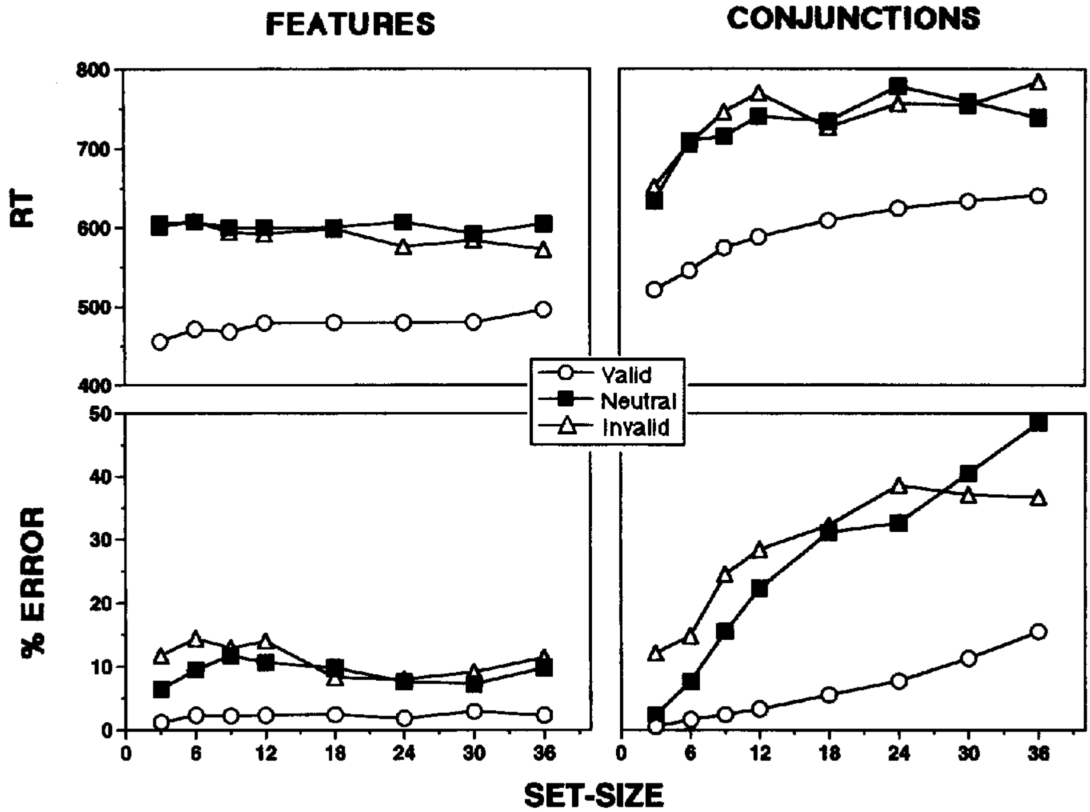

Figure 4. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of set size, under the different cueing conditions (Experiment 1).

set-size effect to be eliminated when the target is attended; because the target location is known in advance, no search would be needed. The finding that the set-size effect was not eliminated questions a serial self-terminating search. Some could object to this finding by postulating that because the cue was valid in only 2/3 of the cued trials, it did not always attract observers' attention to the cued location. However, being an exogenous peripheral cue, it is considered to automatically attract attention to the cued location (e.g., Cheal & Lyon, 1991; Jonides, 1981; Müller & Rabbitt, 1989;

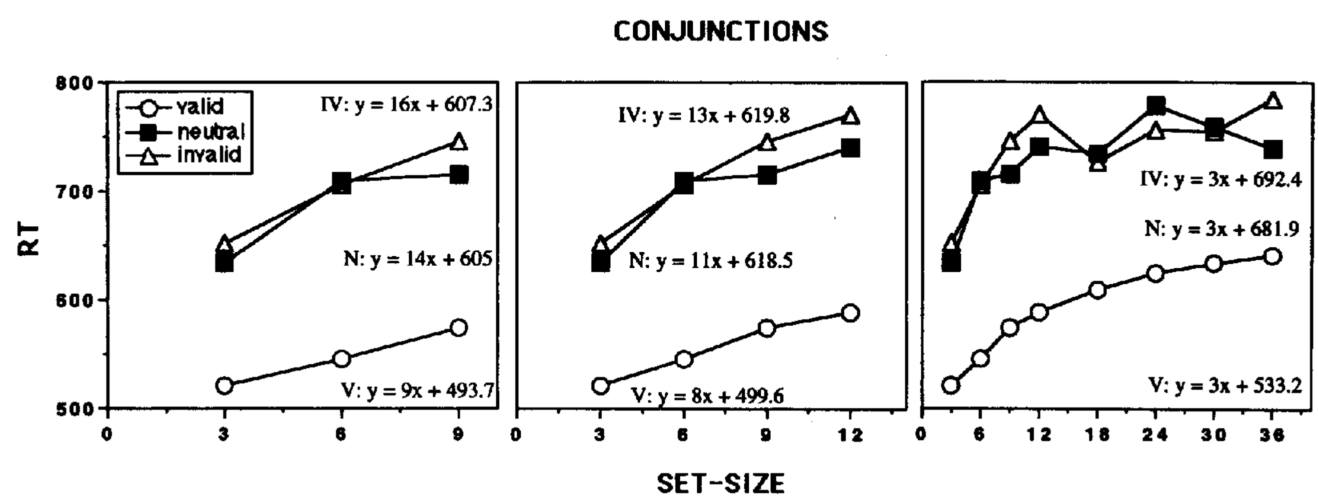

Figure 5. Mean correct reaction time (RT) for conjunction search as a function of different ranges of set size (see text), under the different cueing conditions (Experiment 1). V = valid trials; IV = invalid trials; N = neutral trials.

Nakayama & Mackeben, 1989; Posner, 1980; Remington et al., 1992). Further, because of the large number of possible locations in the display, the cue was also highly informative and encouraged observers to always attend to the cued location. Whereas the cued location had a 0.66 probability of containing the target, any other possible location had a much lower probability (0.028). In addition, the cue would be more informative as set size (and uncertainty) increased. Hence, observers' best search strategy would be to always allocate resources to the cued location. Furthermore, a control experiment (discussed below) indicated that observers could localize the cue effectively throughout the display.

Alternatively, the set-size effect could be accounted for by a parallel, capacity-limited model, in which each additional item is processed at the same time but at a lower rate, as if limited resources were divided among more items (e.g., Kinchla, 1992). Although attending to the target improves overall performance, because the distractors are also processed in parallel they may consume some of the available resources; thus, the more items, the longer the RT and the higher the error rate. In the same vein, previous studies have shown that our ability to ignore irrelevant items is limited (Colegate et al., 1973; B. A. Eriksen & Eriksen, 1974; Mordkoff, 1996; Murphy & Eriksen, 1987). Furthermore, it has been found that distractors affect target identification even when the cue was 100% valid (Chastain, Cheal, & Lyon, 1996).

The interaction of cue and eccentricity. We manipulated covert attention to investigate its effect(s) on the eccentricity effect. Could the allocation of attention to a specific location overcome some of the limitations imposed by the retinal eccentricity? Cue Type × Target Eccentricity interacted (Table 2 and Figure 6); in both search types, the eccentricity effect was smaller when the stimuli were attended but still statistically significant ($p < .001$, except for the error rate of feature search, $p = .1$). The slope analysis confirmed this interaction (Table 2). In both search types, the RT and error rate slopes for the valid condition were significantly shallower than those for the neutral and invalid conditions ($p < .02$), but the RT slopes were still significantly different from zero ($p < .005$).

Table 2
Slopes of the Eccentricity Effect in Each of the Cueing Conditions

Search	Reaction time (ms/item)	Error (%/item)
	Experiment 1	
Feature		
Valid	7.47	0.30
Neutral	26.36	2.10
Invalid	23.29	2.11
Conjunction		
Valid	16.89	0.83
Neutral	35.40	4.82
Invalid	30.35	4.70
	Experiment 3	
Feature		
Cued	3.35	0.44
Neutral	13.00	0.86
Conjunction		
Cued	6.69	0.64
Neutral	18.36	2.50
	Experiment 4	
Conjunction		
Cued	7.6	1.45
Neutral	15.51	2.74

Moreover, RT and error rate Newman–Keuls pairwise comparisons revealed that performance for both features and conjunctions did not differ significantly between valid trials at the most peripheral eccentricity (7.0°) and neutral trials at the most central eccentricity (1.4°). This suggests that directing attention to the most peripheral stimuli could equate performance in the periphery to that of the center and could be considered as analogous to enlarging stimulus size as field eccentricity increases to equate performance for the central and peripheral target locations in detection (Carrasco & Frieder, 1997) and discrimination (Cheal & Lyon, 1989) tasks. Several researchers have asserted that in many visual tasks (e.g., Banks, Sekuler, & Anderson, 1991; Kitterle, 1986; Robson & Graham, 1981; Rovamo & Virsu, 1979), and particularly in visual-search tasks (Carrasco et al., 1995, 1998; Geisler & Chou, 1995), the performance decrement with more peripheral stimuli is due, to a large extent, to the poorer spatial resolution of the periphery. Thus, the reduced eccentricity effect for the detection of the validly cued targets suggests that attending to a stimulus location may improve its sensory representation by enhancing the spatial resolution at the cued location. Nevertheless, the inability of the attentional mechanism to eliminate the eccentricity effect indicates that this mechanism cannot completely overcome the visual system's inherent limitations.

We conducted two experiments to rule out the possibility that the eccentricity effect could not be eliminated simply because of the poorer processing of the peripheral cues at large eccentricities. We presented the bar for 40 ms at all six eccentricities. Eleven observers performed a yes–no detection task. Another 11 observers were asked to localize the bar by indicating in which cell, out of nine possible imaginary square cells, the cue appeared. The target was always present and it appeared at all locations. Observers were instructed to respond as fast and as accurately as possible. ANOVAs showed that neither detection nor localization performance differed as a function of eccentricity and did not follow any systematic pattern. None of the preplanned honestly significant difference (HSD) pairwise comparisons were significant. These findings illustrate that observers could effectively process the cue at all locations.

Experiment 2

The diminished eccentricity effect in the valid condition is consistent with the hypothesis that attention can enhance the sensory representation of the cued location (Bashinski & Bacharach, 1980; Downing, 1988; Posner, 1980; Prinzmetal et al., 1986). Indeed, because the eccentricity effect seems to be accounted for by sensory factors (Carrasco & Frieder, 1997), its magnitude should be modified only if attention

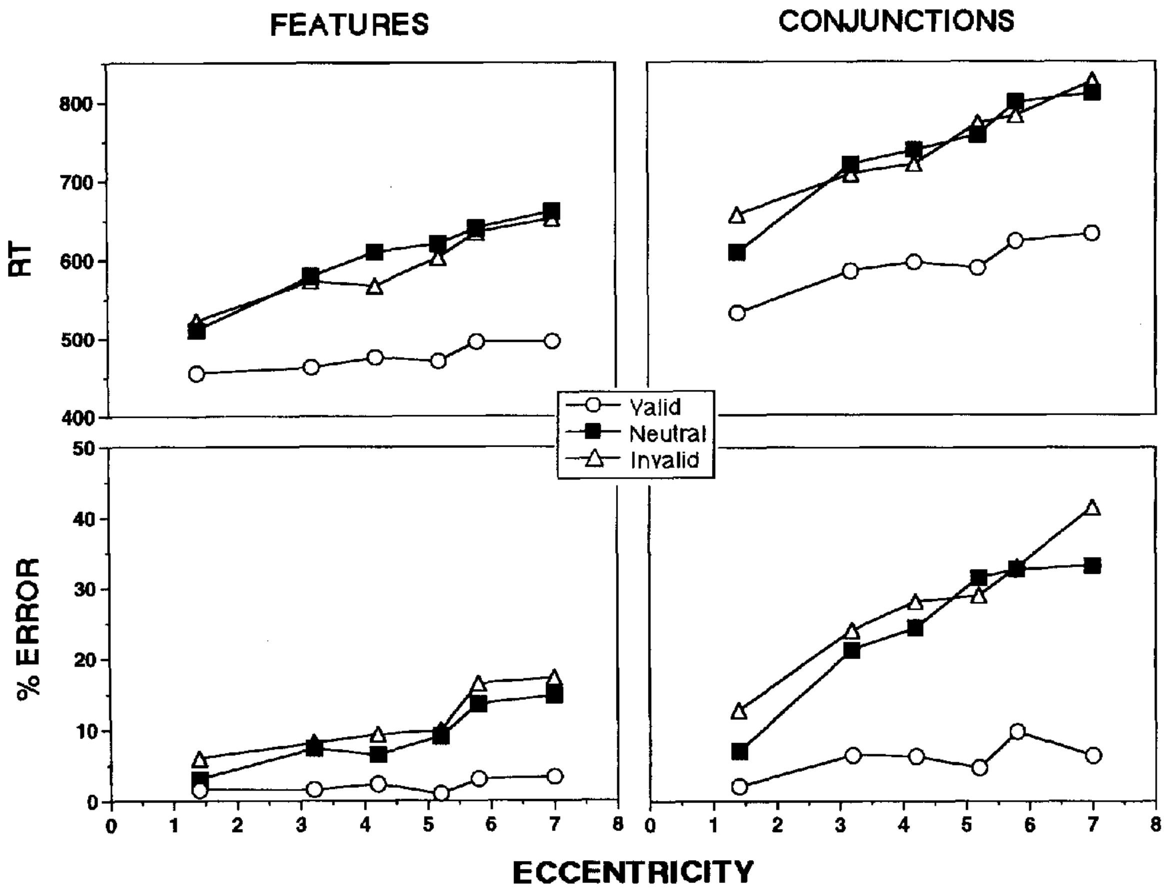

Figure 6. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of target eccentricity, under the different cueing conditions (Experiment 1).

allocation affects early processes. We conducted this experiment to further support this hypothesis and to show that our findings do not merely result from postperceptual effects. For instance, in support of the decision integration view, Kinchla (1992; Kinchla et al., 1995) suggested that the spatial precue does not necessarily improve performance by affecting the quality of the sensory representation. Precueing could lead to the same results by encouraging the observer, while choosing a response, to assign more weight to information extracted from the cued location. Kinchla also suggested that one can distinguish between these two interpretations by presenting a postcue after the presentation of the display but before observers respond. In this manner, the cue would influence the decision-making process but not the extraction or coding of information.

We interpreted that the improved detection of attended targets in the previous experiment was due to enhanced stimulus representation of the validly cued target. To evaluate decision-making alternative explanations, in this experiment we used a postcue to indicate the target location. The only difference between the two experiments was the order of presentation: The peripheral cue was presented after the display. If the postcue produced a similar pattern of results to that of the previous experiment, the improved performance for the valid trials could not be attributed only to enhanced coding of information.

Method

Observers. The observers were 11 undergraduate students from the NYU student pool who did not participate in the previous experiment. All participants had normal or corrected-to-normal vision and were unaware of the purpose of the study.

Apparatus, stimuli, design, and procedure. The apparatus, stimuli, design, and procedure were identical to those in Experiment 1 except that the order of presentation was inverted. In each trial the display was presented first for 94 ms. After an ISI of 54 ms, the cue appeared for 40 ms. This timing was aimed to ensure that when the cue was presented the information had been coded (e.g., Biederman & Ju, 1988; Breitmeyer, 1984; Card, Moran, & Newell, 1986; C. W. Eriksen & Collins, 1967) but a decision had not been made.

Results and Discussion

Given that the main goal of this experiment was to evaluate the effect(s) of postcueing target location on the eccentricity effect, the analyses for the present trials are the most important. A three-way within-observer ANOVA (Cue

Table 3
Experiment 2 Analysis of Variance Results

Factor	*df*	Reaction time *F*	Reaction time *p*	Error *F*	Error *p*
Feature search					
Cue	2, 10	2.11	*ns*	1.88	*ns*
Eccentricity (Ecc)	5, 50	98.25	.0005	28.47	.0005
Set size (SS)	7, 70	1.92	*ns*	2.83	.05
Cue × Ecc	10, 100	1.14	*ns*	<1	*ns*
Cue × SS	14, 140	1.39	*ns*	<1	*ns*
Ecc × SS	35, 350	1.10	*ns*	1.80	.005
Cue × Ecc × SS	70, 700	<1	*ns*	<1	*ns*
Conjunction search					
Cue	2, 10	2.27	*ns*	<1	*ns*
Eccentricity	5, 50	94.32	.0005	18.64	.0005
Set size	7, 70	45.73	.0005	28.34	.0005
Cue × Ecc	10, 100	1.23	*ns*	1.04	*ns*
Cue × SS	14, 140	1.64	*ns*	3.32	.0005
Ecc × SS	35, 350	1.82	.005	2.40	.0005
Cue × Ecc × SS	70, 700	<1	*ns*	<1	*ns*

Type × Eccentricity × Set Size) was performed on mean correct RTs and error rate of these trials (Table 3).

As in Experiment 1, in both feature and conjunction searches, RT and error rate increased as target eccentricity increased (Figure 7). Likewise, in the conjunction search, RT and error rate augmented as set size increased. The highest conjunction error rate, which occurred at the largest set sizes, resulted from the farthest target eccentricities. The main effect of set size was significant for the feature's error rate; a Newman–Keuls pairwise comparison revealed that this difference emerged because there were fewer errors for set-size 3 than for the rest ($p < .05$). Set Size × Target Eccentricity interacted for conjunctions' RT and error rate as well as for features' error rate, confirming that the set-size effect was more pronounced at farther eccentricities.

More important for Experiment 2 is that, as opposed to the strong precueing effect found in Experiment 1, the postcueing effect was not significant, and cueing type did not interact with target eccentricity. Thus, when the cue was presented after the stimuli were encoded, it no longer affected performance. Cue Type × Set Size interacted only for the conjunctions' error rate. There were more errors for the neutral than for the valid and invalid trials ($p < .05$). The lack of a significant difference between the valid and the invalid trials reiterates that the cue did not have a significant effect. Similar results were previously reported for a discrimination task (Lyon, 1990).

In their yes–no detection experiment, Kinchla et al. (1995) found that both a valid precue and a valid postcue enhanced detectability, although the former did so to a greater degree than the latter. Some differences in the experimental designs may explain the different results: For instance, compared with the present experiment, in Kinchla et al.'s experiment, a four-elements array was presented for a shorter exposure duration (15 ms vs. 94 ms), and after a longer ISI (1 s vs. 54 ms), the postcue appeared for a longer time (2 s vs. 40 ms). Kinchla et al. used long delays, aiming to exclude the possibility that the cue could be affecting

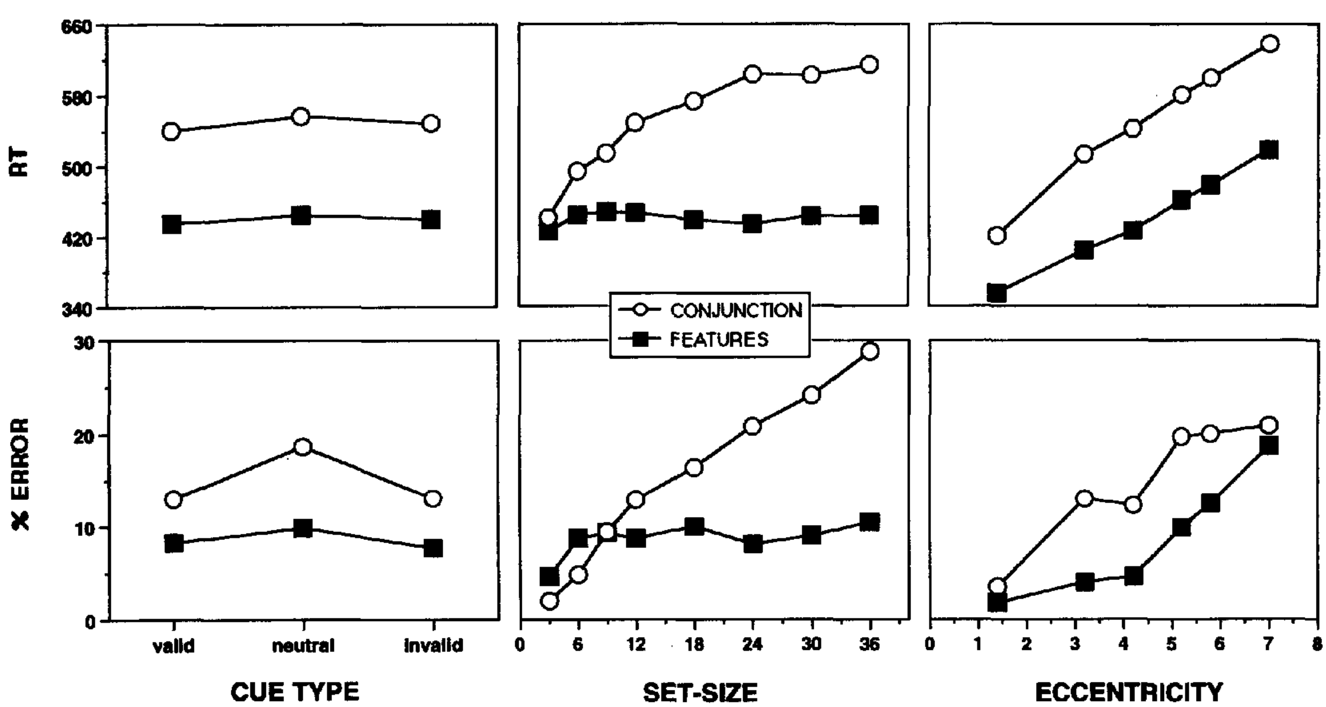

Figure 7. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of cue type, set size, and target eccentricity (Experiment 2).

perceptual processing; however, the sensory information that was extracted from the display might have started to decay, encouraging the observers to rely more on the postcue. Furthermore, given that between 3 s to 6 s elapsed from the array's offset until the observers responded (they had up to 3 s to respond), Kinchla et al.'s results might reflect a greater participation of a memory component.

We did not expect a complete absence of a postcueing effect in the present experiment. As in the previous experiment, the cue was valid on 2/3 of the cued trials; hence, assigning more weight to the cued location (Kinchla, 1992) would have been a useful strategy. The parameters of this postcue manipulation may not have been precise enough to affect decision integration in this experiment. In any case, the failure of the postcue to affect performance does not support the idea that in Experiment 1 the targets were detected more efficiently as a mere result of changes in postperceptual processes. To further support the idea that an enhanced stimulus representation may be responsible for the findings of the previous experiment, we conducted the following experiment.

Experiment 3

Typically, experiments that attempt to directly manipulate attention allocation use cues that indicate that a certain location in the display has a higher probability of containing the target (e.g., Bashinski & Bacharach, 1980; Jonides, 1980; Posner, 1980; Posner et al., 1978). Whereas this high probability is assumed to encourage observers to direct their attention to that particular location, it also poses a difficulty to pinpoint the source of the attentional effect(s). That is, if target detection in the cued location is better than at any other location, it is hard to disentangle whether the enhanced detection is due to facilitation of information coding in that location or simply to the fact that the higher probability encouraged the observers to assign more weight to information already extracted from that location. To disentangle these possibilities, an experimental procedure should encourage observers to allocate their resources to a certain location and ensure that they could not base their performance on differential weights' assignment.

To achieve this goal, in this experiment we used the two-interval alternative forced-choice procedure (2AFC; Figure 8). A trial included two intervals, each consisted of an items' display preceded by a cue. Observers had to decide whether the target was present in the first or the second interval. The cue indicated that if the target was present, it would appear at the cued location. It did not signal which one of the two intervals was more likely to contain the target because both displays were preceded by a cue. Even if more weight was assigned to the cued location, relative to the other locations in each interval, the final decision would have to be based on two equiprobable alternatives: whether the target appeared in the cued location of the first or the second intervals.

In this experiment, observers' best strategy was to always attend to the cued location because the target could appear in only that location. Furthermore, an exogenous peripheral cue is considered to attract attention automatically to its

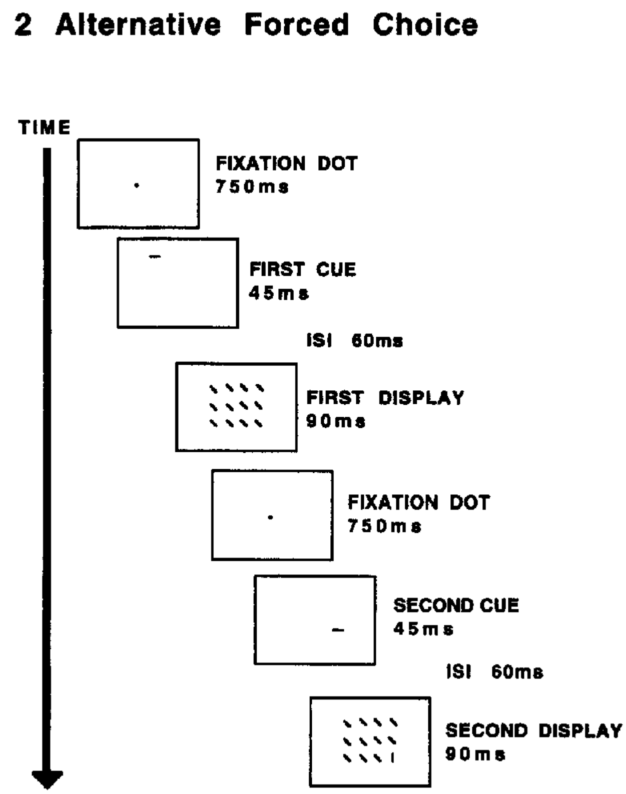

Figure 8. This diagram depicts the sequence of presentation in each trial of Experiments 3 and 4. ISI = interstimulus interval.

location (Jonides, 1981; Müller & Rabbitt, 1989; Nakayama & Mackeben, 1989; Posner, 1980; Remington et al., 1992). Thus, cueing effects found with this cueing procedure would more likely reflect changes at the perceptual level.

Method

Observers. The observers were 12 undergraduates from the NYU student pool who did not participate in the previous experiments. All had normal or corrected-to-normal vision and were unaware of the purpose of the study.

Apparatus. The stimuli were presented on a 15-in. (38.1-cm) monitor of a Power Macintosh 7500/100 computer, whose frame rate equals 15 ms.

Stimuli. The stimuli were the same as those in Experiments 1 and 2 except that there were only six possible set sizes: 3, 6, 12, 18, 24, and 30.

Design. Half the trials were cued trials in which the horizontal bar appeared above the target location in the "present" interval, and above a nontarget location in the "absent" interval, which only included distractors. The bar never appeared in the same location in the two intervals that made up a trial. The other half of the trials were neutral trials in which the circle appeared in the center of the display in both intervals. The target appeared equally often (50% of the time) in each interval. Observers performed a feature task in one 1-hr session and a conjunction task in the other session. Each observer performed a total of 1,152 trials. The order of presentation of the experimental sessions was counterbalanced, and the order of the trials within a session was randomized.

Table 4
Experiment 3 Analysis of Variance Results

Factor	*df*	Reaction time *F*	Reaction time *p*	Error *F*	Error *p*
		Feature search			
Cue	1, 11	7.34	.05	4.27	.063
Eccentricity (Ecc)	5, 55	4.45	.005	3.51	.01
Set size (SS)	5, 55	3.98	.005	2.32	.056
Cue × Ecc	5, 55	<1	*ns*	<1	*ns*
Cue × SS	5, 55	<1	*ns*	<1	*ns*
Ecc × SS	25, 275	<1	*ns*	2.22	.005
Cue × Ecc × SS	25, 275	<1	*ns*	1.01	*ns*
		Conjunction search			
Cue	1, 11	20.09	.001	38.44	.0005
Eccentricity	5, 55	11.50	.0005	11.31	.0005
Set size	5, 55	52.84	.0005	29.34	.0005
Cue × Ecc	5, 55	7.78	.0005	6.89	.0005
Cue × SS	5, 55	3.74	.01	10.24	.0005
Ecc × SS	25, 275	1.60	.05	1.43	*ns*
Cue × Ecc × SS	25, 275	1.28	*ns*	1.67	.05

Procedure. The observers were read instructions specifying the target, advising them to fixate on the fixation point throughout the experiment and asking them to indicate, as rapidly and accurately as possible, whether the target was present in the first or second interval. Figure 8 illustrates the presentation sequence in each trial of the 2AFC procedure. In each of the two intervals, first the bar or the circle appeared for 45 ms, and after an ISI of 60 ms, the display was presented for 90 ms. The second interval was presented 750 ms after the offset of the first display. Observers responded by pressing a key on the computer keyboard with the index or middle finger of their dominant hand. Half the observers used their index finger to indicate that the target was present in the first interval, and the other half used their middle finger. Immediately after the observers responded, the appropriate feedback sign was presented for 750 ms. There were 96 practice trials before each experimental session.

Results and Discussion

A three-way within-observer ANOVA (Cue Type [cued vs. neutral] × Eccentricity [1.4° to 7.0°] × Set Size [3 to 30]) was performed on mean correct RTs and error rates of the present trials (Table 4 and Figure 9). As in Experiment 1, the peripheral cue was successful. Features and conjunctions were detected faster and more accurately in the cued than in the neutral trials. The eccentricity effect found for both search types illustrates the robustness of this effect. Also, as in the previous experiments, performance in conjunction search decreased significantly as the number of items in the display increased. This was also the case for feature search. A similar generalization of the set-size effect to a 2AFC has been reported previously (Palmer, 1994; Palmer et al., 1993).

The central motivation for this experiment was to examine whether directing attention in advance to the target location with the 2AFC procedure would exhibit the same results as the yes–no task of Experiment 1. We were mainly interested in the interactions of cueing type with the other factors. The patterns of these interactions were similar to those obtained in Experiment 1 (Table 4 and Figure 10). The

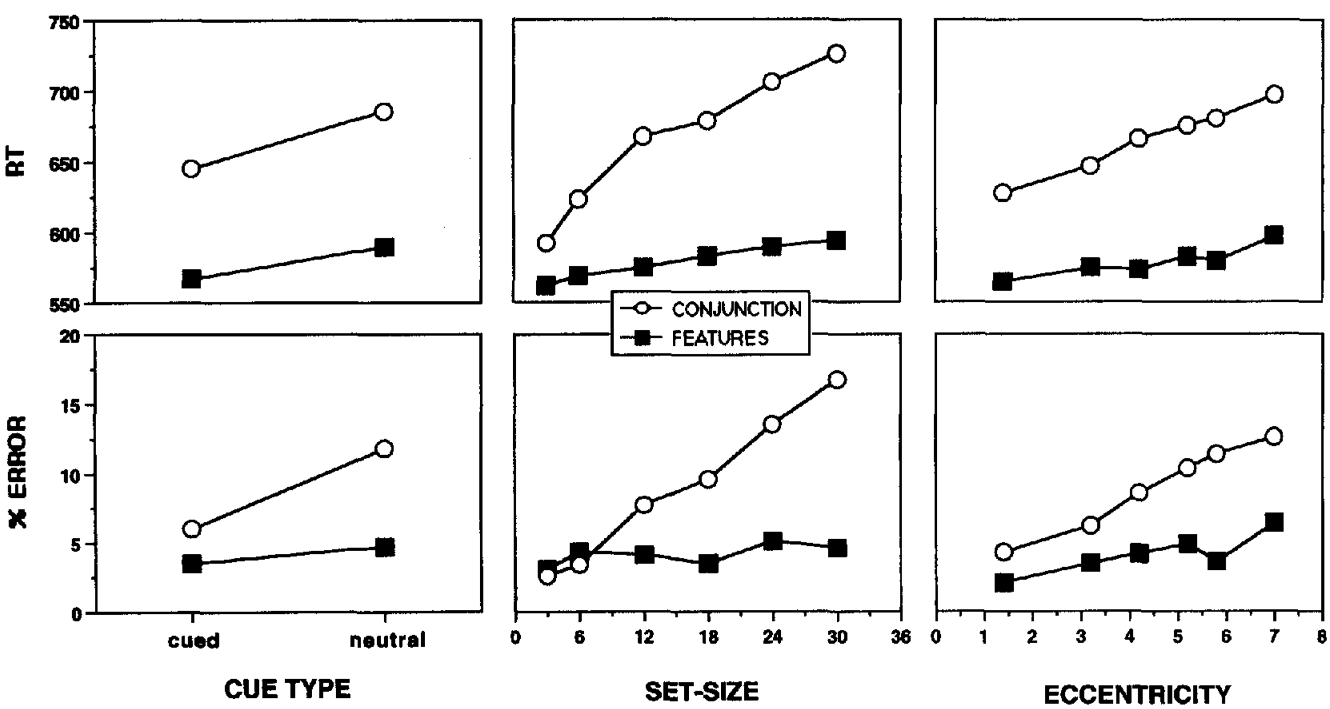

Figure 9. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of cue type, set size, and target eccentricity (Experiment 3).

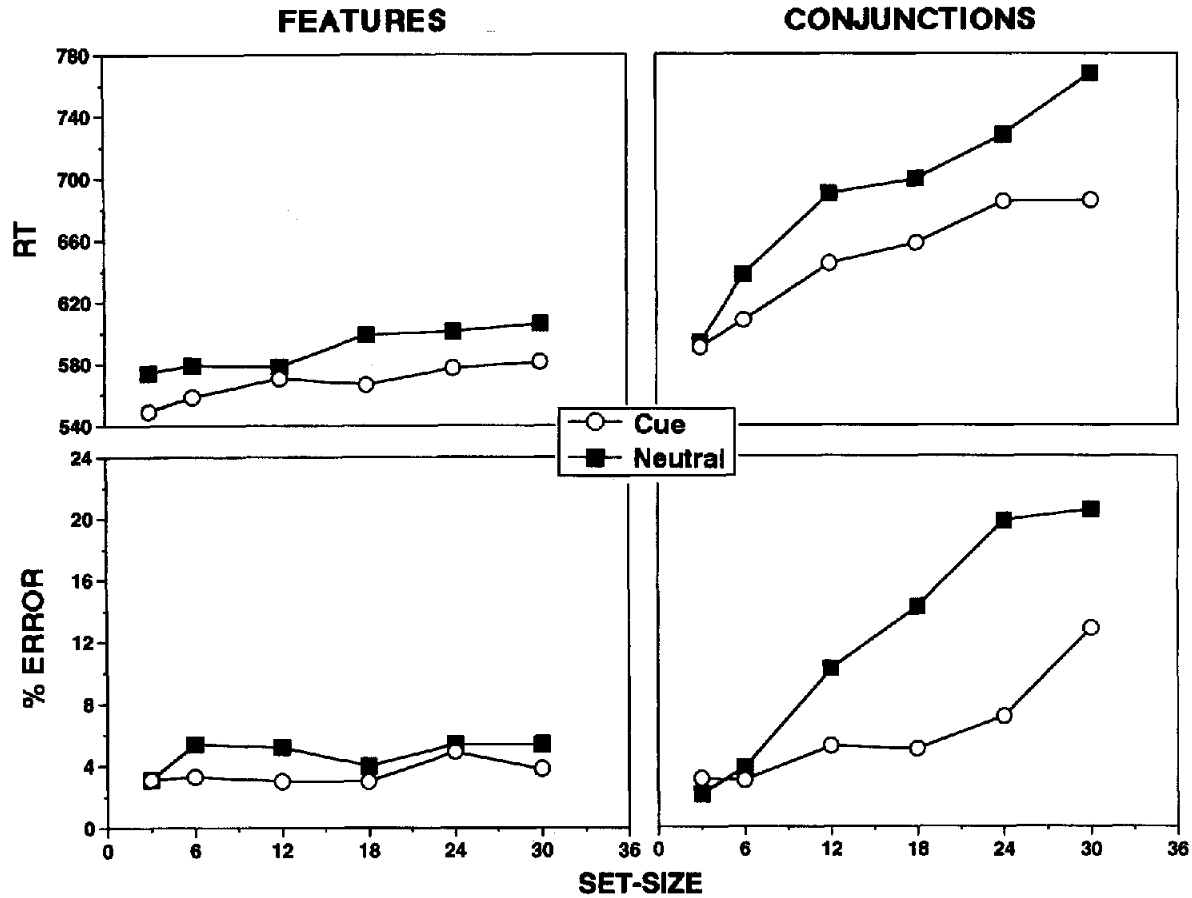

Figure 10. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of set size, under cued and neutral conditions (Experiment 3).

RT and error rate conjunction interactions between cueing and set size were significant. In the cued trials, the set-size effect was not eliminated, only reduced; RT and error rate slopes were significantly different from zero ($p < .02$). Thus, the inability to eliminate the set-size effect by directing attention to the target location in a 2AFC procedure corroborates the findings of the yes–no task of Experiment 1.

Similar to Experiment 1, there was a significant interaction between cueing and target eccentricity (Table 4 and Figure 11). The magnitude of the conjunction eccentricity effect was significantly reduced for the cued as compared with the neutral trials, yet still significant ($p < .05$). Although the feature interaction was not significant, a preplanned comparison revealed that the eccentricity effect was significant in the neutral trials but not in the cued trials. The slope analysis confirmed these findings (Table 2). In both search types, the RT and error rate slopes of the cued trials were significantly shallower than those of the neutral trials ($p < .03$), but still significantly different from zero ($p < .05$). In sum, directing attention to peripheral locations, even when the cue was not conveying helpful information as to the interval that contained the target, reduced the differences between detection of peripheral and central targets. Given that this reduction in the eccentricity effect cannot be solely attributed to modifications in the decision processes, it provides convergent evidence to the idea that covert attention improves performance by enhancing the sensory representation.

Finally, the conjunction three-way interaction emerged because the difference in the magnitude of the set-size effect at different eccentricities was smaller in the cued than in the neutral trials (Figure 12). Moreover, Set Size × Target Eccentricity interacted in the neutral (RT and error rate, $p < .03$) but not in the cued trials. This reduction provides further evidence for the confound between the set-size and the eccentricity effects. Attending to the targets reduced the eccentricity effect, possibly by enhancement of the spatial resolution, which resulted in a smaller set-size effect, especially at large eccentricities. That is, attending to the targets removed to some degree the set-size effect component that has been attributed to spatial resolution (e.g., Carrasco et al., 1995; Carrasco & Frieder, 1997) and reduced the differences in the magnitude of the set-size effect at different eccentricities.

Although a consistent pattern of results emerged from experiments using different methodologies (Experiments 1 and 3), to further generalize our findings we conducted two other experiments by using the same 2AFC methodology as in the present experiment. In one experiment, 11 observers

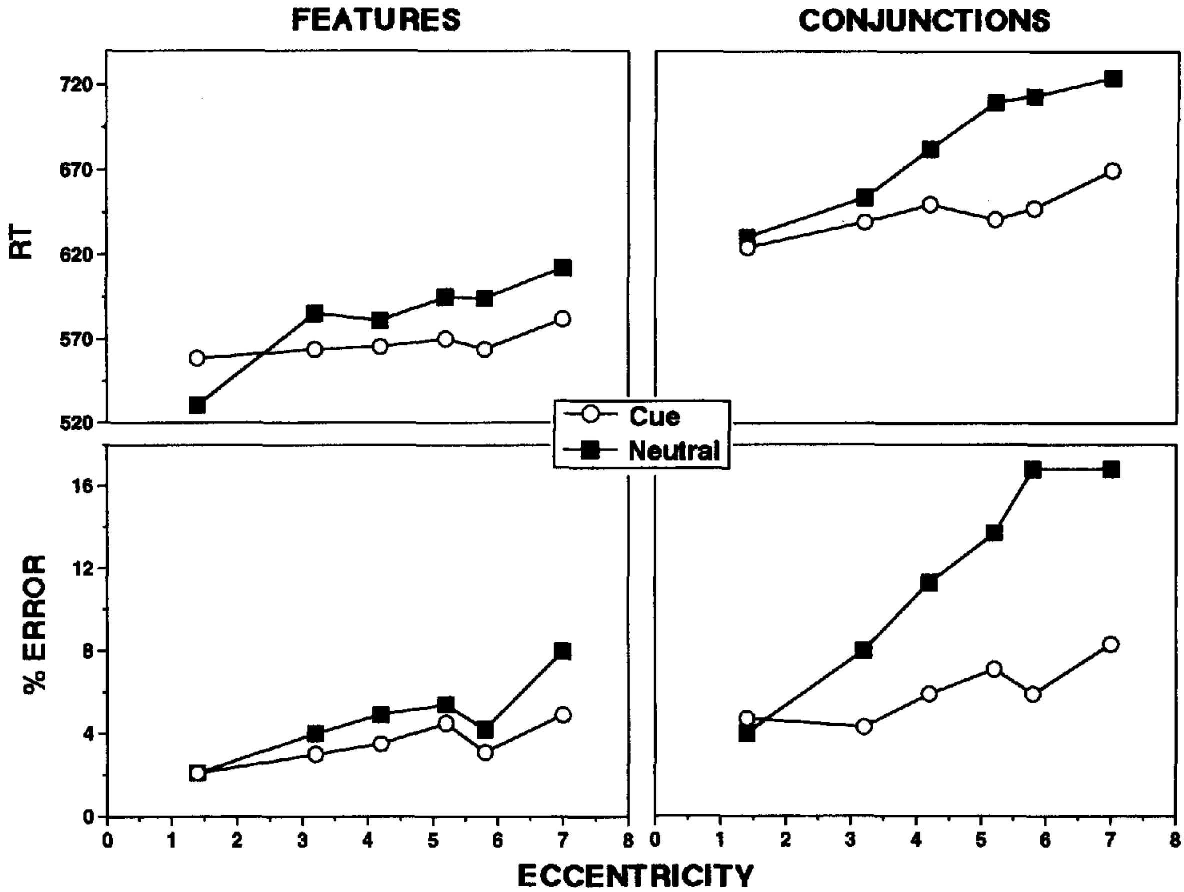

Figure 11. Mean correct reaction time (RT) and error rate for feature and conjunction searches as a function of target eccentricity, under cued and neutral conditions (Experiment 3).

searched for a Color × Shape conjunction: a red V target among blue Vs and red inverted V distractors. In the second experiment, 9 observers searched for a red mirror image L-like target among red 180° counterclockwise rotated Ls and red 90° clockwise rotated L distractors, which is a task found to be highly serial (e.g., Duncan & Humphreys, 1989). The results of these three experiments were highly consistent with the findings of Experiment 3; both the set-size and the eccentricity effects were less pronounced in the cued than in the neutral trials, but not eliminated.

Experiment 4

Given that the interval between the cue and the display used in the previous experiments was derived from previous estimates of covert attentional shifts (Bergen & Julesz, 1983a; Saarinen & Julesz, 1991; Sagi & Julesz, 1987; Tsal, 1983), it was presumably sufficient for attention to focus on the cued location. Nevertheless, to ensure that the interval between the cue and the display had not been too short for the cue to have an optimal effect, in the present experiment we lengthened this interval to the point where the cue would still be effective (Cheal & Lyon, 1992b; Nakayama & Mackeben, 1989) and eye movements could not take place during an interval (Mayfrank et al., 1987).

Method

Observers. The observers were 12 NYU students who did not participate in the previous experiments. All had normal or corrected-to-normal vision and were unaware of the purpose of the study.

Apparatus. The stimuli were presented on a 17-in. (43.18-cm) monitor of a Power Macintosh 7500/100 computer, whose frame rate equals 13.4 ms.

Stimuli. The stimuli were the same as those in the conjunction search of Experiment 3.

Design. The design was the same as in Experiment 3, except that each observer performed a total of 576 conjunction trials in one 1-hr session.

Procedure. The procedure was the same as that of the previous experiment, except that the ISI between the cue and the display was twice as long. In each of the two intervals of the 2AFC procedure (Figure 8), the bar or the circle appeared for 40 ms, and after an ISI of 121 ms the display was shown for 94 ms.

Results and Discussion

The pattern of results obtained here using a longer ISI than in the previous experiment was highly similar. A three-way within-observer ANOVA (Cue Type × Eccentricity × Set Size) was performed on mean correct RTs and on error rates of the present conjunction trials (Table 5).

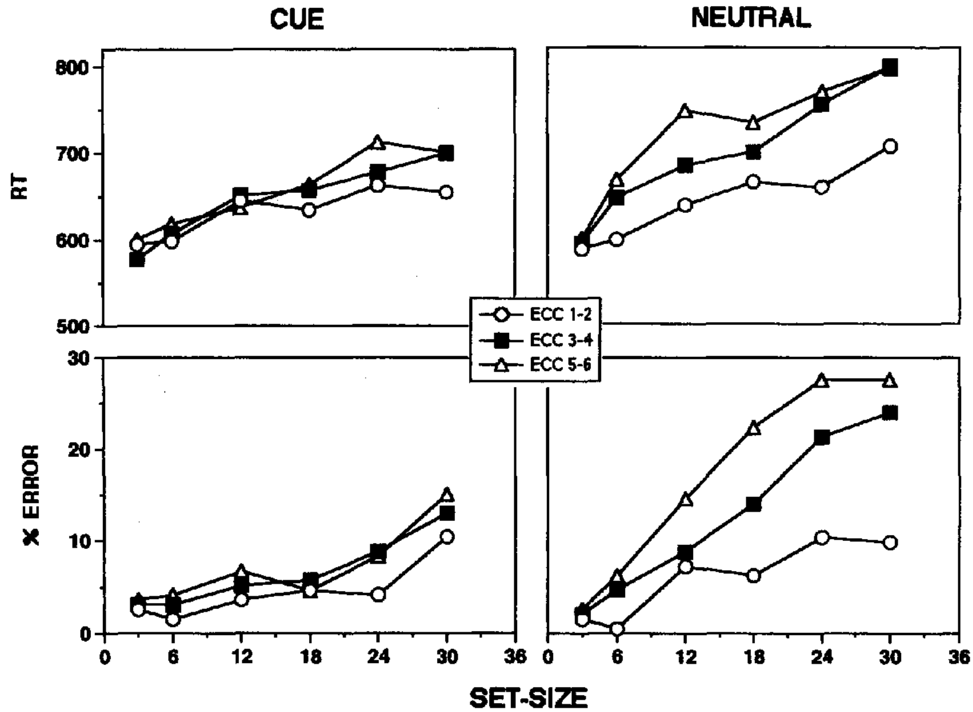

Figure 12. Mean correct reaction time (RT) and error rate for conjunction search as a function of set size and target eccentricity, under cued and neutral conditions (Experiment 3). ECC = eccentricity.

Search was more accurate for the cued than for the neutral trials, and both RT and errors increased as the target appeared at more peripheral eccentricities and as the number of items in the display increased.

As in Experiments 1 and 3, the RT and error rate interactions of cueing type and the two other factors were significant. The set-size and the eccentricity effects were lessened for the cued as compared with the neutral trials (Figure 13). However, the set-size effect was still significant for the cued trials (RT and error rate, $p < .0001$), and RT and error rate slopes were significantly different from zero ($p < .01$). This result supports the findings of Experiments 1 and 3 that showed that directing attention to the target location failed to eliminate the set-size effect. Likewise, the eccentricity effect was still present in the cued trials (RT, $p < .01$; error rate, $p < .0001$). The slope analysis validated this finding (Table 2). The RT and error rate slopes of the cued trials were significantly shallower than those of the neutral trials ($p < .05$), but the RT and error slopes were still significantly different from zero ($p < .005$).

In conclusion, even though the temporal interval between the cue onset and the display onset was doubled in this experiment, as compared with the previous ones, and cue validity was 100% (when the target was present, it always appeared at the cued location), peripherally precueing the target location reduced, but did not eliminate, either the set-size or the eccentricity effects.

Table 5
Experiment 4 Analysis of Variance Results

Factor	*df*	Reaction time *F*	Reaction time *p*	Error *F*	Error *p*
Conjunction search					
Cue	1, 11	2.47	.14	21.79	.001
Eccentricity (Ecc)	5, 55	7.66	.0005	14.26	.0005
Set size (SS)	5, 55	30.92	.0005	24.47	.0005
Cue × Ecc	5, 55	2.68	.05	5.06	.001
Cue × SS	5, 55	2.77	.05	3.03	.02
Ecc × SS	25, 275	1.67	.05	2.33	.001
Cue × Ecc × SS	25, 275	<1	*ns*	<1	*ns*

General Discussion

A consistent pattern of results emerged from all experiments in which attention was directed by a peripheral precue: When attention was directed to the target location, for both feature and conjunction searches, overall performance improved and the eccentricity effect was reduced, although not eliminated. The set-size effect found for the conjunction search was also reduced (except in Experiment 1's RT), but was not eliminated.

Cueing Effect

The precue manipulation resulted in improved detection of the attended stimuli (Figures 3 and 9). For conjunctive targets, this was not surprising. Several models of visual search postulate that a conjunction search requires covert attention, either because attention is the mechanism that combines features into a single object (e.g., Treisman, 1993;

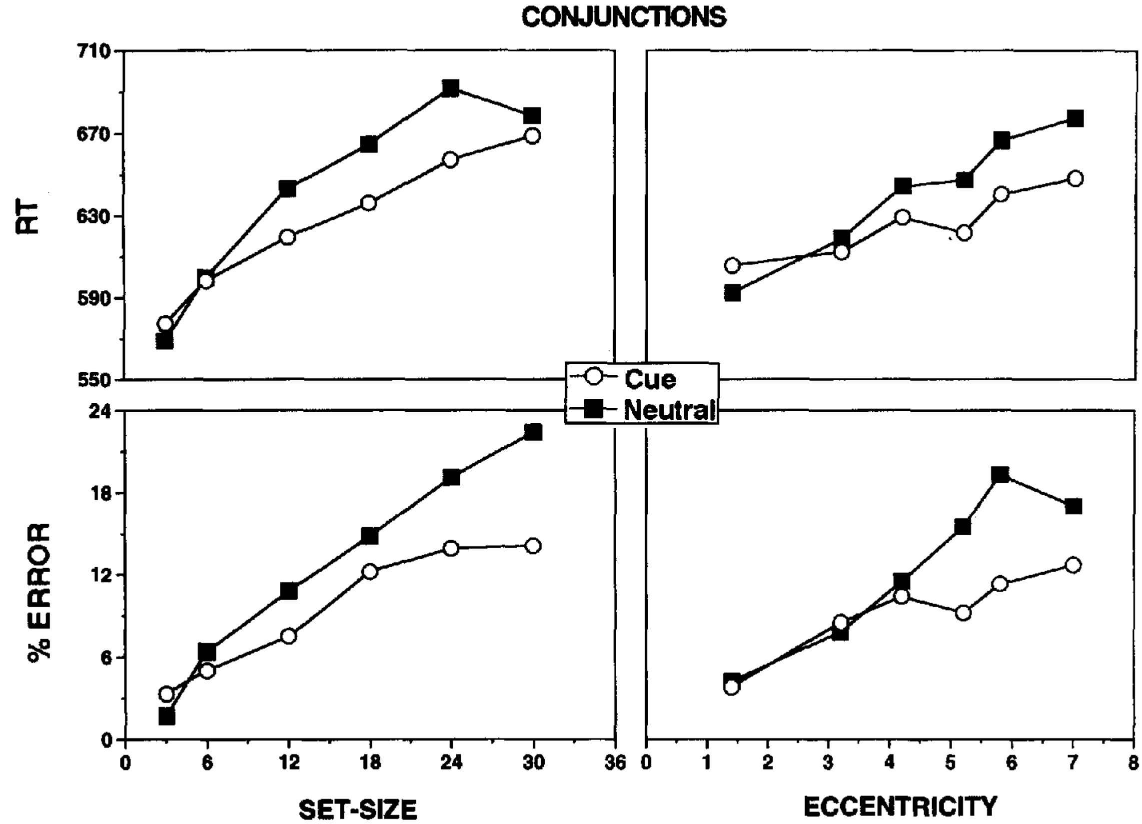

Figure 13. Mean correct reaction time (RT) and error rate for conjunction search as a function of set size and eccentricity, under cued and neutral conditions (Experiment 4).

Wolfe, 1994) or because such a target shares attributes with the distractors, and hence, it has to compete for access to the visual short-term memory (VSTM), where it can become the "focus of current behavior" (Duncan & Humphreys, 1989, p. 446). The improved detection of features, which is in line with previous findings (Cheal & Lyon, 1992b; Kim & Cave, 1995; Prinzmetal et al., 1986), would be harder to explain according to models of visual search that consider feature coding to be strictly preattentive, that is, to take place before resources are allocated selectively (e.g., Duncan & Humphreys, 1989; Treisman & Gelade, 1980; Wolfe et al., 1989).

The improvement in feature detection of a vertical line among tilted lines could be predicted by the revised FIT (Treisman, 1993; Treisman & Gormican, 1988). These authors have stated that vertical lines are "standard values" and tilted lines are "deviating values"; whereas detecting a vertical line demands attentive processing that would result in a serial search, detecting a tilted line does not require attentive processing and would result in a parallel search. In Experiment 1, however, there was a significant benefit for the attended feature targets, although the set-size effect was not significant (Table 1), which according to visual-search models indicates attention participation. This finding, together with previous studies (e.g., Carrasco et al., 1995; Carrasco & Frieder, 1997; Cheal & Lyon, 1992a; Townsend, 1972, 1990), questions the validity of the set-size effect as an index of covert attention and calls for clarification of the term *preattentive.* This term seems to have two different connotations: The process can be performed without attention, and the process should not benefit from attention allocation because it precedes any selection. We suggest that the term *preattentive* should be used only when performance does not benefit from attention allocation.

In any case, the fact that attention allocation benefited the detection of features, presumably coded in an early stage of information processing (e.g., Duncan & Humphreys, 1989; Treisman & Gormican, 1988; Wolfe, 1994), suggests that attention could facilitate early visual processes. This idea receives support from the fact that performance improved only when the cue was presented before the display. Once the cue was presented after the display (Experiment 2), so that it could no longer affect information coding, performance did not differ between cued and neutral targets. The possibility that attention can modify early visual processes is especially viable in light of the attentional facilitation obtained with the 2AFC procedure in which the peripheral cue did not indicate which interval was more likely to contain the target (Experiments 3 and 4). This procedure ensured that observers could not base their response on differential weights' assignment. The improved detection of the cued targets may have resulted from an enhanced sensory representation at the cued location.

The Interaction of Cue and Target Eccentricity

The specific nature of this enhancement could be inferred from the finding that precueing the target location diminished the differences in detection performance among the distinct retinal eccentricities (Figures 6, 11, and 13). Thus, an enhancement of the spatial resolution at the retinal region corresponding to the attended location may be one of the factors underlying the improved performance that is commonly observed for cued items. Moran and Desimone (1985), for instance, have found that when an "effective stimulus" that normally elicits a strong neural response is unattended, the neural response is greatly reduced if a "noneffective stimulus" in the same receptive field is attended. These authors have suggested that attention contracts the receptive field and that this contraction may result in higher spatial resolution (Desimone & Ungerlieder, 1989; Desimone et al., 1990; Moran & Desimone, 1985; Olshausen et al., 1993).

As we expected, precueing the target location did not neutralize the eccentricity effect. This suggests a limit to the magnitude of resolution enhancement caused by the attentional mechanism. The inability of the attentional mechanism to eliminate the eccentricity effect sheds light on the nature of this effect. It has been proposed that the inferior detection at farther target eccentricities reflects the order of attentional deployment. Because attention is biased to the central locations, the serial search begins with the most central items and continues to the more peripheral ones (Wolfe & O'Neill, 1995). Combining this line of reasoning with the finding of enhanced performance at cued locations (e.g., Bashinski & Bacharach, 1980; C. W. Eriksen, 1990; Van der Heijden, 1992) would predict an elimination of the eccentricity effect for the cued trials. The biased allocation of attention to central items should be overcome by directing attention to a peripheral cued location because the search would always start at the cued location. The present findings, however, did not fit this prediction; they supported a spatial resolution explanation of the eccentricity effect (Carrasco et al., 1995, 1998; Carrasco & Frieder, 1997).

The Interaction of Cue and Set Size

Another difficulty for the common interpretation of the set-size effect is posed by the fact that directing attention in advance to the target location did not cancel the set-size effect (Figures 4, 10, and 13). Most visual-search models invoke covert attention to account for performance decrement as the number of items increases (e.g., Duncan & Humphreys, 1989; Palmer, 1994; Treisman, 1993; Wolfe, 1994). It would follow then, that once attention is directed to the target location, the set-size effect would be eliminated. For instance, according to the tenets of FIT (e.g., Treisman, 1993; Treisman & Gelade, 1980; Treisman & Gormican, 1988) and GSM (e.g., Wolfe, 1994; Wolfe et al., 1989), when the target location is known in advance there would be no need for a sequential focusing of attention. Regardless of the number of items in the display, attention would be allocated directly to the target, and set size should not affect performance.

Palmer and colleagues (1994; Palmer et al., 1993) proposed an alternative attentional explanation for the set-size effect. They attributed this effect to the increased risk of confusing the target with a distractor as the number of distractors increases (see also Kinchla, 1974; Shaw, 1982). In Palmer and colleagues' design, as the number of items in the display was kept constant, a different number of items was cued as relevant in each trial. They interpreted the finding that the magnitude of the relevant set-size effect was similar to the magnitude of the display set-size effect as reflecting that attention underlies search performance. Following this line of thought, regardless of the actual set size, cueing only one location would be similar to a search with relevant set size of one, and performance should not be affected by the number of items in the display.

Finally, Duncan and Humphreys (1989, 1992) suggested that set size affects performance because for an item to become the "focus of current behavior" (p. 446), it must gain access to the VSTM. Display items compete for the limited access to the VSTM, and assignment of resources to a particular item augments its access probability. Consequently, if the target location is known in advance, one would allocate all resources to the cued target, which then would have the highest VSTM access probability, and performance should not be affected by set size.

In the present study, the set-size effect was not eliminated, even though, as the following points illustrate, the precue successfully directed covert attention to the target location: (a) Overall performance for the cued targets improved significantly. Had observers in Experiment 1 based their answers on the mere presence of the cue, target detection would have not differed between the valid and the invalid trials. Moreover, the 2AFC procedure prevented this possibility, and target detection was still more efficient for the cued than for the neutral trials. (b) The cue was highly informative. In Experiment 1 the probability of the target appearing at the cued location was much higher (.66) than at any other location (.028). In Experiments 3 and 4, the target could appear only at the cued location. In both experiments, the pattern of results was very similar. (c) Peripheral cues, like the one used in the present study, are considered to capture attention in an automatic manner (Jonides, 1981; Müller & Rabbitt, 1989; Posner, 1980; Posner & Cohen, 1984; Remington et al., 1992; Yantis, 1996). (d) The interval between the cue and the display provided enough time for the attentional mechanism to travel even to the furthest eccentricity (e.g., Bergen & Julesz, 1983a; Cheal & Lyon, 1992b; Lyon, 1990; Nakayama & Mackeben, 1989; Saarinen & Julesz, 1991; Sagi & Julesz, 1987; Tsal, 1983). Furthermore, when this interval was doubled (Experiment 4), the pattern of results was the same. (e) The spacing between the items in this study, 2° of visual angle, was larger than the estimated space needed for attention to prevent distractors' interference (1° of visual angle; e.g., C. W. Eriksen & Hoffman, 1972b; Murphy & Eriksen, 1987). (f) A consistent pattern of results emerged from experiments using different methodology (yes–no and 2AFC) and different stimuli (orientation feature, Color × Orientation Conjunction, Color × Shape Conjunction). In short, the results obtained in the present study pose serious difficulties to visual-search models, which assume that the set-size effect reflects a serial allocation of attention.

To conclude, this study showed that the set-size effect does not result from only the serial deployment of attention. When attention was directed to the target location, neither the set-size nor the eccentricity effects were eliminated, only decreased. A possible role of covert attention in visual search may be inferred from the finding that when the eccentricity effect was reduced, that is, for the cued targets, the difference in the magnitude of the conjunction set-size effect for distinct target eccentricities diminished as well (Figure 12). Similarly, when the stimulus size was magnified (according to the M-factor; Virsu & Rovamo, 1979), the eccentricity effect was eliminated, and the set-size effect was diminished and constant across retinal eccentricities (Carrasco & Frieder, 1997). Thus, we suggest that covert attention may indeed enhance the stimulus perceptual representation and that this enhancement diminishes the eccentricity effect, which in turn reduces the set-size effect.

The finding that covert attention was not completely effective in excluding the processing of the unattended, nonrelevant items supports a model that assumes limited capacity, parallel processing (see also McElree & Carrasco, 1998). Such a model would permit an improved target detection at the attended location, as well as processing of unattended items. On the basis of the evidence gathered so far, this model should take into account sensory factors, such as spatial resolution and lateral inhibition (e.g., Carrasco et al., 1995, 1998; Carrasco & Frieder, 1997; Geisler & Chou, 1995; Verghese & Nakayama, 1994), and cognitive factors, such as the existence of an attentional mechanism that facilitates the processing of relevant information by enhancing its perceptual representation.

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